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Research Article

Kinematic Analysis of the Ankle Joint During Fatigue

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Abstract

Objective: This study aims to investigate fatigue induced kinematic changes of the ankle joint on recreational runners on a three-dimensional level in a controlled running laboratory environment.

Design: Experimental study

Setting Gait lab, sports department, University Hospital of Antwerp.

Participants: 12 male recreational runners.

Assessment: All runners completed a one-hour treadmill run with a running pace predetermined by sports medical assessment to ensure fatigue was induced.

Main Outcome Measures: Physiologic parameters and a subjective fatigue scale ensured that fatigue was reached. Kinematic data in three dimensions were obtained by a pressure plate and infrared camera observation of 33 markers placed on the body and shoes.

Results: All the participants reached fatigue. The measurement of step time parameters before and during fatigue showed no significant difference in this study group. Regarding ankle kinematics defined in three dimensions no significant differences before and during fatigue were found.

Conclusion: Fatigue was induced successfully in all the participants after completing the fatigue protocol. No statistically significant changes were observed in the kinematics of the ankle of recreational runners, nor in the step time parameters.

Clinical Relevance: As there is no significant change in ankle kinematics after fatigue is induced in recreational runners, the focus of prevention of RRI is more likely to be found elsewhere.

***Keywords:** Kinematics, Ankle joint, Fatigue, Running*

Introduction

Nowadays, physical activity on a daily level is promoted for a healthy lifestyle. A sedentary lifestyle brings different kinds of strains along the way (1). As running is a low threshold, easily accessible sport which is promoted by the national health council, it is flowering every year. In Flanders (Belgium) running is the most popular sport amongst adults, and about 30% of the sportive flemish people does running (2). On the downside of the health benefit, running is related to a high incidence of running related injuries (RRI), mainly concerning the lower limb (3). These injuries are primarily found with recreational runners (4, 5). Predisposing qualities for development of running related injuries include high body mass index (BMI), previous injuries and no history of training in sports with load on the axial skeleton (3). Fatigue have a big influence on changes in running gait pattern. Fatigue can be defined as a subjective feeling of tiredness combined with objective measurable muscle fatigue. In order to define changes in running gait pattern during the phase of fatigue, more specifically in the ankle joint, muscle fatigue needs objectivation.

Literature review shows no consensus method to quantify fatigue. Therefore 6 different methods are withheld: I) Cardiovascular/anaerobic model II) Energy supply/depletion model III) Neuromuscular model IV) Muscle damage model V) Thermoregulatory model VI) Psychological/motivational model (6, 7).

In the cardiovascular/anaerobic model fatigue is defined as reaching threshold limits for 3 different parameters: 85% of the maximal heart rate (220 – age), 90% of the maximal VO2 and 4 mmol/l lactate for the anaerobic threshold workable in study participants.

Different sources suggest a change in running gait kinematics following physical and mental fatigue. Muscles responsible for stabilization of pelvis and core cannot develop the necessary power in state of fatigue and therefore influence the kinematics. Control of the body gravity point over the loaded leg can be load and a different gait pattern rises (8, 9).

Not only does fatigue influences kinematics, the stance and swing time while running differ as well. Previous running experiments on a treadmill have shown an increase in swing time and a decrease in stance time when fatigue occurs. The step length was increased as well. The subjects alter their gait pattern with an increase in swing time as the treadmill passes underneath them. This makes running on a treadmill easier but cannot be applied to field running (10). Another study showed that subjects who were running 24 hours on a treadmill decreased their stance time significantly, what secondary increased their mean step frequency at stage of fatigue (11).

Changes in kinematics of the lower limb while running on a treadmill during state of fatigue are described by Dierks et al. Significant differences were found concerning foot eversion, internal rotation of the knee and tibia and peak velocity for hip adduction. A small decrease was found in peak velocity for knee flexion. There were no significant differences found concerning the hip angles (12).

A study concerning differences in statics in 2 dimensions showed a significant increase in ankle angle during state of fatigue (13). This difference in eversion was already described by Koblbauer, however in this study the change in gravity point and core instability were more pronounced (5). The result of muscle fatigue was tested on a group of trained military men. This study resulted in a decrease in ankle dorsiflexion at heel contact during state of fatigue (14).

The lack of research of normal kinematical changes of the body during state of fatigue raises questions. The result of running in a state of fatigue in a healthy population group of recreational runners was not yet described in 3 dimensions. In order to make predictions on predisposition for injuries, the kinematics of the ankle joint should be defined in 3 dimensions, as well as their differences in state of fatigue.

Methods

Subjects

All subjects were exposed to a sport's medical examination by a sports physician, as well as an exercise test on a treadmill guided by an exercise physiologist. If no medical contra-indications for heavy exercises, the subjects were allowed to enter the study. Based on the results of 5 subjects, a power analysis was made with software G-power 3.1.9.2. and calculated a minimal sample group of 13 subjects. In total, we achieved a number of 18 subjects who participated our study between January 2014 and March 2015. All subjects were healthy young men between the age of 23 and 41 years old and complied with the inclusion criteria. The experiment found place in the gait laboratory of UZA SPORTS.

Table 1: Inclusion and exclusion criteria subjects

Inclusion Criteria	Exclusion Criteria
Male	Use of orthesis
Age: 18 – 45y	
BMI: 18,5 – 25,0 kg/m^2	Fail on sports medical examination
Recreational runners	
Normal gait pattern	History of surgery, diseases on joints of lower limb or chronic back pain
Heel or midfoot runners	
Neutral running shoe	
Voluntary participation / Informed consent	

As there is a difference in muscles and biomechanics between men and women, this study is limited to the male gender to eliminate gender differences on kinematics (15, 16). Related to overweight, the subject will be selected within the age range of 18 to 45y and with a BMI within healthy standard [18,5-25,0 kg/m2].

As our goal is to study a normal running pattern, we only selected subjects with a neutral running shoe who land on their heel- or midfoot at initial contact. We also choose to select recreational runners as it would otherwise be too difficult to achieve fatigue within the limited test period. Every subject is aware of the risks and signed the informed consent.

Exclusion criteria included history of surgery, chronic pain and/or acute injuries to lower limb. The use of orthosis and a failure at the sports medical examination excluded these subjects as well.

Of our 18 healthy young men, 2 had an abnormal ECG in rest. Although they were approved by a heart specialist, we did not include them in our study. 1 subject had excessive sweating and therefor lost too many markers during the test which made his results not reliable. 3 other subjects had technical issues while processing their results. Finally, we ended with 12 subjects for ankle kinematics and 15 for processing of physiological parameters.

Materials

In order to measure anthropometry and the weight of the subject prior to the running test, we used a caliper, measuring tape, a balance and a stadiometer.

The study was conducted on a treadmill with a built-in force plate of Biometrics® to record vertical ground reaction forces (VGRF). This treadmill was positioned in the middle of the gang lab, surrounded by an eight-fold 3D camera system from Vicon® for registration of the 3D kinematics. Analog video images were taken by 2 high-speed cameras (Basler®), one in line with the treadmill for a posterior view and one on the left for a profile view. The test subjects were asked to run in bare upper body, short running pants and in heel socks with their own running shoes. On the eve of the test, they were asked to shave their legs so that the markers would stick better. We positioned 33 reflective markers on the skin according to an adapted Vicon Nexus® plug-in-gait model on anatomical marker points (Figure 1).

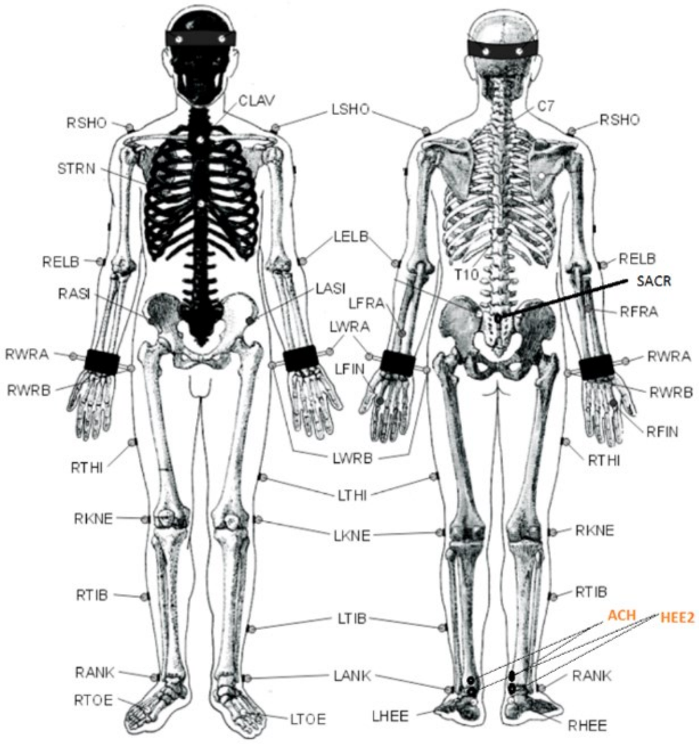

Figure 1: Markers plug-in-gait model and extra added heel markers (ACH and HEE2).

In addition to the plug-in-gait model, 2 extra markers were placed bilaterally on the skin at the achilles tendon (ACH) and at the transition of the heel and the achilles tendon (HEE2). To prevent the markers from loosening during walking, they were fixed to the skin with Micropore® and Leukotape®. Dermabond® skin glue was used for the markers on the ankle and knee. The reflective areas on the running shoes were covered with covering tape. In addition to the markers, the subject was equipped with a Polar® chest strap (heart rate registration) and an ergo spirometry mask (Hans Rudolf) to measure oxygen uptake (Metalyzer II, Cortex®). The right earlobe of the subject was rubbed with a hyperemizing ointment (Algipan) in preparation for a 20-microliter blood test with an end-to-end capillary. Immediately after collection, the filled capillaries were placed in an eppendorf cup filled with 1 ml perchloric acid whereby the blood underwent complete hemolysis. The lactate concentration in the blood samples was determined immediately after the test via Biosen Clinic Line®, EKF.

The kinematics data were processed with Vicon® software and Matlab® on a PC with Windows 7®.

Procedure

Prior to the study, all subjects underwent a sports medical examination and exercise test according to the UZA SPORTS protocol. Before the start of the 1-hour running on test day, height and weight were measured again. The anthropometry was also measured, being the leg length and width of the knee, ankle, elbow and wrist. These parameters are required for the processing of the 3D kinematics in the software program. With the exception of both knee markers, all markers were applied in accordance with the plug-in-gait model with adjustment as shown above in Figure 1. The static calibration was done stationary on the treadmill using a Knee Alignment Device (KAD), after which both knee markers were also applied. The fatigue protocol was then started, consisting of 5 phases (Table 2).

Table 2: Fatigue protocol

Phase	Time (min)	Activity	Measuring
Phase 1	0 - 3	Standing still	3D kinematics, VGRF, lactate, spirometry, RPE borg scale, heartrate
Phase 2	3 – 8	Walking	3D kinematics, VGRF, lactate, spirometry, RPE borg scale, heartrate
Phase 3	8 – 68 (measure every 5min)	Running at predefined pace	3D kinematics, VGRF, lactate, spirometry, RPE borg scale, heartrate
Phase 4	68 – 73	Walking	3D kinematics, VGRF, lactate, spirometry, RPE borg scale, heartrate
Phase 5	73 – 76	Standing still	3D kinematics, VGRF, lactate, spirometry, RPE borg scale, heartrate

The parameters (3D kinematics, VGRF, lactate, spirometry, RPE Borg scale, heart rate) and analogue images were recorded at pre-agreed times. The 3D kinematics and VGRF were recorded over a period of 5 gait cycles. Before taking the blood sample from the earlobe, the subject jumped on the sides of the treadmill using ropes to make this happen safely. At the end of the fatigue protocol, all markers, heart rate monitor and ergo spirometry mask were removed.

Outcome measures

Step time parameters

Previous study showed the change of step time parameters when fatigue occurs. While running on a treadmill the stance phase will decrease while the swing phase will increase. The parameters measured are step time, stance time and swing time.

Ankle kinematics

Since we want to objectify the movements of the ankle joint in the context of later further investigation into possible predisposition to walking injuries, we opt to examine the parameters in the stance phase. For this we determine the minimum and maximum angle in position, and the angle during landing and offset. We determine these 4 parameters in 3 planes: sagittal, frontal and transversal. For the angles in frontal plane, an adjustment was made on the software to obtain a more detailed result. By convention we determine all these angles on the right foot of the test subject.

Physiological parameters

The measured physiological parameters are ventilation (VE), oxygen uptake (VO2), carbon dioxide (VCO2), respiratory quotient (VCO2 / VO2), lactate concentration, heart rate (HR) and the score on the Borg scale (RPE). The choice of these parameters was determined by the simplicity of the measurements during exercise, so that the test subjects are minimally disrupted during exercise.

Figure 2: *a. Frontal: inversion/ eversion b. Sagittal: dorsiflexion, plantarflexion c. Transversal: internal-/external rotation*

Analysis

Statistical analyzes were performed with SPSS Statistics 16.0® and 22.0®. For the ankle kinematics we did a before / after analysis where the results were placed in 2 columns (start and end of phase 3), where the 1st measurement for fatigue was recorded (start of phase 3) and the 2nd measurement during fatigue (end of phase 3). To determine whether our results meet the normality assumption, the Shapiro-Wilk test was used for all results. With normal distribution, the paired T test was used to do the before / after analysis. If not distributed normally, the Mann-Whitney U test was used. A p value <0.05 was considered to be statistically significant.

Ethical Consideration

All participants voluntary completed the fatigue running protocol after a thorough sports medical examination and exercise test on a treadmill.

Results

Demographic results

Our population included men only with an average age of 27.9 years (SD 5.7 years), an average height of 1.81 m (SD 0.06 m) and an average weight of 76.2 kg (SD 8.8 kg). All test subjects were recreational athletes with moderate endurance training. This is derived from the measured VO2max during the exercise test of 51.6 ml.kg-1.min-1 (SD 4.5 ml.kg-1.min-1) and especially the maximum running speed on the treadmill of 15.4 km.h -1 (SD 1.2 km.h -1). The average number of days between the sport's medical examination and the fatigue test was 23 days.

Physiological results

For 1 hour our 15 subjects ran on a treadmill at a speed of 11.5 km/h (SD 0.9 km.h -1) corresponding to 67.1% (SD 8.8%) of their VO2 max and a lactate concentration of 4.2 (SD 1.5 mmol / l). One subject had to stop early (after 40 minutes instead of 60 minutes) because of physical incapacity to continue.

During the running test, an average of 79.4% (SD 2.5%) of the maximum heart rate (measured during the previously taken exercise test) was achieved. The fatigue level, indicated via the Borg scale, increased during the hour of running from a resting value of 6-7 / 20 to a maximum of 18/20 (SD 1.0) at the end of the test.

Table 3: Physiological results

Parameter	Mean + SD
Running speed	11.5 ± 0.9 km/h
% maxVO2	67.1 ± 8.8 %
Lactate level	4.2 ± 1.5 mmol/l
Mean HR as % maxHR	79.4 ± 2.5%
Peak HR as % max HR	94,5 ± 2,5
RPE	18/20 ± 1

Step time parameters

Begin- and end values for the step time parameters are shown in table 4. None of these described parameters showed a significant difference before and after the endurance test.

Table 4: Results step time parameters

	Before fatigue	In state of fatigue	Difference	P-value
Steptime R	0,37 (± 0,02) s	0,39 (± 0,04) s	0,02 (± 0,04) s	0,127
Stance R	0,27 (± 0,02) s	0,29 (± 0,10) s	0,02 (± 0,10) s	0,233
Flight R	0,47 (± 0,03) s	0,48 (± 0,04) s	0,01 (± 0,03) s	0,548

Kinematic parameters

The right ankle was examined in three areas: sagittal, frontal and transversal. The angle of the ankle with the treadmill during stance phase was observed. We made the calculation specifically for the minimum and maximum angles in stance and the angles at foot off and foot strike. Statistical processing did not show us significant differences for the above calculated angles.

Table 5: Ankle kinematics

		Minimal Angle at Stance	Maximal Angle at Stance	Angle at Footstrike	Angle at Foot Off
Sagittal	Before	-6,06 ± 6,62 °	28,35 ± 4,04 °	11,14 ± 7,70 °	-6,05 ± 6,56 °
	After	-7,55 ± 6,06 °	28,46 ± 4,20 °	12,35 ± 6,36 °	-7,54 ± 6,05 °
	Difference	-1,49 ± 3,96 °	0,11 ± 1,91 °	1,21 ± 2,83 °	-1,49 ± 3,45 °
	P-value	0,453	0,529	0,773	0,419
Frontal	Before	149,68 ± 9,53 °	168,35 ± 2,94 °	159,74 ± 11,00 °	150,29 ± 9,20 °
	After	151,11 ± 8,47 °	168,52 ± 3,90 °	161,46 ± 5,81 °	150,82 ± 7,61 °
	Difference	1,43 ± 8,58 °	0,17 ± 1,86 °	1,72 ± 7,94 °	0,53 ± 8,83 °
	P-value	0,908	0,954	0,954	0,954
Transversal	Before	-26,04 ± 9,89 °	-13,45 ± 9,36 °	-12,99 ± 13,22 °	-13,37 ± 13,38 °
	After	-25,70 ± 9,87 °	-12,88 ± 10,05 °	13,32 ± 14,15 °	-11,44 ± 13,17 °
	Difference	0,34 ± 2,01 °	0,57 ± 3,80 °	-0,33 ± 3,80 °	1,94 ± 4,15 °
	P-value	0,58	0,862	0,773	0,525

Discussion

In this study, 15 subjects ran on a treadmill for 1 hour at a speed of 74.5% (SD 3.1%) of their maximum running speed during the previously taken exercise test. The speed at which to run was determined by the sports physiologist on the basis of the course of the lactate curve, the maximum values during the previously taken exercise test and on the basis of the recent sport history of each subject.

The question is whether the exercise led to (physical) fatigue in the test subjects.

The literature shows that fatigue is multifactorial and cannot be clearly defined. The most commonly used definition describes muscle fatigue as a temporary decrease in the capacity to deliver physical exertion (17). Because in this study we had the participants stop after 1 hour of exercise, we can only objectify fatigue by comparing a number of measurements before and after.

The change in RPE score suggests that the test subjects were tired ($p < 0.01$). In addition, an average lactate concentration of 4.2 mmol.l -1 (SD 1.5 mmol.l -1) and the maximum lactate concentration indicated 6.1 mmol.l -1 (SD 2.3 mmol.l -1) during the 1-hour exercise also involves a physically demanding exercise ($p < 0.01$). In an overview article from Billat, maximum lactate steady state values of 3.9 mmol / l (SD 1.0 mmol / l) are reported. This was recorded during exercise on the treadmill over a time period of 40 minutes to 1 hour (18). The results in our study are even slightly higher. The highest heart rates were achieved at the end of the 1-hour walking test, partly as a result of the cardiovascular drift phenomenon as a result of the fluid loss (1.2 +/- 0.4 kg or 1.6 +/- 0.6% of body weight) (19). 94.5% (SD 2.5%) of the previously measured maximum heart rate was achieved. These parameters also indicate a physical exertion that led to fatigue.

In previous research, the ankle joint of recreational runners in fatigue was already examined in two dimensions by HD video images (13). Conducting the same research in three dimensions is a steppingstone to a later new study. Based on the results from our pilot study, it can then be checked which factors predispose for injuries. From literature research we already know that the ankle is a preferred location for the development of injuries. There is a suspicion that increasing the angle of eversion during fatigue contributes to this (20). It was therefore important for us to focus on this ankle joint.

In a recent article by Koblbaur et al, changes in the ankle joint have already been described in case of fatigue. This involved an increase in eversion angles. Although subtly present (change of 1.3 ° on average), they were found to be significant (5). The changes in angle of eversion were only significant for the non-dominant leg, although for the dominant leg there was no significance, but a trend towards change. The study by Dierks et al also described this eversion, but here no difference was made between the dominant and non-dominant leg. The average eversion angle here was on average 1.5 ° (12). There are also significant differences in the internal rotation of the tibia (5, 12). Given the link between the joints in biomechanics, this has led us to believe that there should be differences in the transversal plane of the ankle as fatigue occurs.

However, our study did not show a significant difference in the ankle kinematics before and during fatigue. If we look at the obtained differences in the angle of eversion of the ankle. The obtained differences in the angel of eversion of the ankle in our study are similar/comparable to other studies (rerenties toevoegen). The confidence intervals in our study suggest that there is a large spread in results and that a larger study population could help. A box plot of the differences suggests that although no statistical significance has been found, further research could provide more clarity.

A number of factors must be taken into account. The number of test subjects in our research population is too small according to the calculated power analysis to obtain a significant result. This is a result of all kinds of factors. First of all, we had to exclude 2 test subjects because they did not pass the sports medical examination. Subsequently, the registration with one test subject failed while walking, due to skin sloughing which caused markers to come off and thus give a distorted image. Given the importance of the ankle markers for our study, we fixed these with … to ensure their position during the test with Dermabond® skin glue. This is to ensure that the ankle markers would stay on site throughout the effort. Three subjects were excluded related to errors generated during the software analysis, so that these results were no longer usable. An error occurred, and therefore confirmed markers could not be distinguished from ghost markers.

It has been known before that men and woman have a different muscle and skeleton configuration (15, 16). In the study of Buist, a training schedule was drawn up according to the start-to-run principle, for both men and women. This study showed that a quarter of the runners developed a "running related injury" during the 8-week training period, and that men were more often injured than women (4). The correct cause of this was insufficiently investigated. Given the gender-dependent results of this study, we chose to include only male subjects in our study.

The search for suitable test subjects was not always easy; on the one hand due to the inclusion and exclusion criteria and on the other hand due to the length of the test and fear of the strenuous effort of the candidates. Because of this we have chosen to include 4 test subjects with a BMI between 25.0 and 26.0.

We placed the markers directly on the skin of the test subject, except on the foot and ankle. Three of the five foot / ankle markers were attached to the shoes. Although we took into account the fact that the test subjects were not allowed to wear corrective shoes or soles, the effect of shoes in itself is sometimes somewhat misleading for the results found. It has already been described that attaching markers to shoes could overestimate or underestimate the angles (21). In our study it was not possible, as we could not let the test subjects run barefoot for 1 hour. A line of thought that was taken in advance was the subjects before and after the effort to get the shoes off. The disadvantage of this was that the markers would not be stuck exactly in the same place before and after exercise. A second problem was that the fatigue effect on the ankle could be partially lost during this change.

Another difficulty we encountered was the disappointing quality of the HD cameras. With this we should be able to make a good difference between heel, midfoot and forefoot runners. The forefoot runners can easily be identified, but the distinction between heel and midfoot runners was not always very clear. Determining the gait pattern in this way is very subjective. A solution for this is to investigate the force pattern in foot landing, which is very different for heel and midfoot runners (22).

As described earlier, step time parameters change as a test subject becomes more tired. The swing time becomes longer and the stance time therefore shorter. However, this only applies to walking on a treadmill, because more treadmill will go underneath you due to a longer swing and you will therefore have to make less effort to achieve your result (10, 11). Although in our study subjectively a very different gait was noted during the recordings before and during fatigue, we could not substantiate this with our data.

Conclusion

A clear change in physiological parameters was recorded. This change indicates a fatigue provoked by the effort. Despite this objective status of fatigue, we cannot find a significant difference in parameters of step time and ankle kinematics before and during fatigue.

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We have no financial disclosure or conflicts of interest with the presented material in this article.

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