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# Effect of ankle plantar flexors fatigue on force production and running parameters

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# Abstract

Our study focuses on the effect of ankle plantar flexors fatigue on force production and running parameters.

Muscle fatigue is defined as a reduction of maximal strength or power of the muscle. It develops gradually soon after the onset of sustained activity and does not correspond to the moment when it is unable to maintain a task.

We used two different fatigue protocols of the ankle flexor muscles:

1) The isokinetic apparatus (the gold standard), a device which is bulky, expensive and time consuming for tests. The isokinetic fatigue protocol induces fatigue by performing maximal isokinetic contractions.
2) The single-leg Heel-Raise, which is a simple, cheap and fast for testing. The Heel-Raise fatigue protocol is a combination of concentric and eccentric loading of the plantar flexor muscle. When a subject is performing a Heel-Raise protocol, he moves his body mass against gravity.

Then we assessed the effects of the two fatigue protocols with two different methods:

1) Analytic clinical way: effects of fatigue on force. We used a hand-held dynamometer (HHD), for the recording of the strength of maximal voluntary contractions (MVC).
2) Functional way (Running): effects of fatigue on running parameters. We used a treadmill for the recording of qualitative parameters (running economy).

The aim of our study was to compare the effect of functional Heel-Raise induced fatigue versus isokinetic induced fatigue protocols on MVC and on running economy.

For the time being, available clinical evaluations are only done in static or running mode, but without pre-fatigue considerations.

In total, 18 subjects participated in the study. The study was conducted over two days of testing at the Hôpital de la Tour in Meyrin (GE). The participants considered for the study practice physical activities from moderate to vigorous level, are healthy and without known cardiovascular or metabolic comorbidities.

Regarding the effects of the two fatigue protocols on force production and running economy, we noticed that our fatigue protocols do not fatigue as much as initially thought. Nevertheless, we observed a few pre and post test differences on strength and running economy. Differences were mainly observed between men and women.

Key words: Muscle Fatigue, Plantar Flexor Muscle, Fatigue Protocol, Running Economy, Muscle Force, Sport Medicine.

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# 1 Introduction

## 1.1 Fatigue and risk factor for runners [1]

Formerly, fatigue was defined as a reduction induced by exercise in muscular ability to produce strength or power. This independently whether the muscle was able to maintain or not a task [2] [3].

More recently, Enoka and Duchateau [4] have noticed in this definition that it was important to differentiate between muscle fatigue and the ability to continue the task. Muscle fatigue develops early and gradually after the onset of the sustained physical activity and does not correspond to the moment when it is unable to maintain a task. Muscle fatigue is a reduction of maximal strength or power.

Fatigue is divided into peripheral fatigue (muscle) and central fatigue (nervous system, upstream of neuromuscular junction). It is impossible to separate central fatigue from peripheral fatigue. An influence of one will have an impact on the other.

Peripheral fatigue is characterized in a decrease of the contractility of the muscle fiber due to biochemical changes in the working muscle [5]. It is a reduction of the ability of the muscle to produce torque by altering the system at the level of the neuromuscular junction, distally to it [6]. In particular, this corresponds to a decrease in the propagation of the action potential through the neuromuscular junction and along the muscle fiber, as well as excitation-contraction changes within the muscle fiber [7] [2] [8].

Central fatigue is a percentage decrease in the maximal voluntary activation (% VA) [9]. Prolonged exercise is associated with a decrease in % VA [10]. Central fatigue is a failure of the central nervous system (CNS) to recruit motor units at a discharge rate that corresponds to the frequency of the tetanic fusion. In other words, it's a decrease of the discharge frequency upstream from the frequency of the tetanic fusion and a decrease of recruitment of motor unit; both factors leads to a decrease in maximal voluntary contraction. Central fatigue is not as simple as it seems to be, and it seems that environmental conditions such as hypoxia and hyperthermia, as well as mental fatigue can exacerbate central fatigue [11] [12] [13]. The influence of central fatigue is very variable on total fatigue [14].

Most running injuries are overload injuries related to suboptimal practice (too much, too soon, too often). Therefore, the fatigue of certain muscle groups and muscle-tendons complexes suffers the consequences. We find mainly the following pathologies: muscular spasm / tear of the calf complex (flexors of the ankle), shin splints, tendinopathy of the Achilles or plantar fasciopathy. The extrinsic risk factors which play a major role for such pathology development are a lack of specific experience in sport practice, insufficient muscular preparation and the type of material used.

The optimization of tissue resistance capacity under the specific running load is essential in order to optimally prevent the intrinsic risk factors, like reduction of flexibility and strength, fatigue etc. In such context, a clinical assessment of the risk factors for runners would be key, especially with regards to muscle fatigue.

## 1.2 Foot ankle flexors are affected by fatigue related injuries

Running can induce fatigue of the foot ankle flexors, respectively the ankle dorsi-flexors (DF) or the plantar-flexors (PF). This fatigue varies depending on the duration, the number of repetitions and the intensity. Another criteria, especially in long distance running, is the surface type. Downhill running causes more injuries to the foot, ankle and lower leg than level running. This comes from the greater eccentric muscular contractions imposed by downhill running. In contrast, uphill running causes a shortening of the locomotor muscles to produce force, which leads to an increase in energy consumption and leads to higher metabolic fatigue [15] [16] [17] [18] [1].

Predominant running fatigue at the PF level, and not at the DF level, has been observed by many authors. This is due to the fact that it is during the stance phase that we have the major activity of the PF [19].

This increase of lower leg muscle fatigue is directly correlated with an increase of muscular injuries.

There is a marked variability in the use of the terminology relating to muscle injury, with the most prevalent inconsistencies for the term “strain”. A new comprehensive classification system was developed [20], which differentiates between four types:

- functional muscle disorders, describing disorders without macroscopic evidence of fiber tear:
    - Type 1 : overexertion-related
    - Type 2 : neuromuscular muscle-spindle disorders
- structural muscle injuries with macroscopic evidence of fiber tear, that is, structural damage:
    - Type 3 : partial tears
    - Type 4 : (sub) total tears/tendinous avulsions

The occurrence circumstances and pain characteristics drive the physician to make a diagnosis with one of the above listed injuries.

## 1.3 Fatigue protocols and assessment of the fatigue

### 1.3.1 Fatigue protocol

In our study, we used two different fatigue protocols for the ankle flexor muscles.

1. Isokinetic
2. Heel-Raise

These protocols are described below.

#### 1.3.1.1 Isokinetic

Fatigue protocol of the ankle flexor muscles with an isokinetic apparatus (Cybex with the Humac Norm Software from the Hospital La Tour, Meyrin, Geneva): this is the gold standard, but the device is bulky, expensive and the test is time consuming.

This protocol induces fatigue by performing a maximal isokinetic contraction. In 1997, the evaluation of sustained isokinetic contraction has been demonstrated by Vollestad [21] as the most common method for testing or inducing muscle fatigue.

It is mandatory to monitor the force output produced by the isokinetic contraction. The force can be either at a predefined level or at the maximum contraction force. The problem with this type of contraction is that we do not know the behavior of the muscle during the execution of the movement, when the physiological functions as well as the biomechanical functions change. Furthermore, there is more than one muscle working as an agonist for the desired movement, it is therefore difficult to induce functional fatigue by isokinetc contraction [22] [23].

Our fatigue protocol is also used and validated as a fatigue test. But in our study, it is used to induce a muscle fatigue and not for testing muscle fatigue.

#### 1.3.1.2 Heel-Raise (HR)

Fatigue protocol of the ankle flexor muscles with a single-leg Heel-Raise (HR). This is a simple, cheap and fast test.

The Heel-Raise fatigue protocol is a combination of concentric and eccentric loading of the plantar flexor muscles [24], therefore an isokinetic exercise. When a subject is performing a Heel-Raise protocol, he moves his body mass against gravity [25]. Our protocol induces fatigue by making a sequence of movements of the plantar flexor muscles through a full range of motion (RoM) of the ankle until the requested work can no longer be performed to achieve a pre-set RoM. Our protocol still suffers from subotimal reliability and repeatability, because of the difficulty to respect precise RoM limits and therefore performance measures can be dependant on the tester. The use of accessory muscles and the fact that the muscles of the lower leg must maintain a static and dynamic balance while performing the task are also limitations of the protocol [23].

In 1995, Lunsford and Perry [25] showed that this fatigue protocol could be used and validated as a standard test of the function of plantar flexors and that 25 Heel-Raises repetitions are considered as normal.

### 1.3.2 Fatigue assessment

The following two methods are used to assess the effects of the two fatigue protocols:

1. Analytic clinical way (HHD): effects of fatigue on force
2. Functional way (Running): effects of fatigue on running gait parameters

These assessments are described in the next sections.

#### 1.3.2.1 Analytic clinical way (HHD): effects of fatigue on force

The hand-held dynamometer (HHD) recorded the strength of maximal voluntary contractions (MVC) by a muscle as it contracts whilst pushing against a fixed object. HHD is a crucial tool used clinically to measure muscle strength for specific joint angle in fixed static positions, therefore an isometric contraction. HHD cannot measure the properties of dynamic muscle performance, it does not measure the full range of motion (RoM). HHDs are tools that are inexpensive, easily configurable, small and portable, and require little user-specific software knowledge. Despite these advantages, HHD is dependent on the tester's technique [26] and experience [27] [28] [29] [30].

### 1.3.2.2 Functional way (Running): effects of fatigue on running parameters

We used a treadmill and breathing gas analysis for the recording of qualitative parameters (running economy).

Each subject was equipped with a mask that allows to calculate the running economy by analyzing the inspired air and exhaled.

The running economy is one of the parameters of aerobic performance, like the maximum oxygen consumption (VO2 Max), endurance, or oxygen uptake kinetics.

#### 1.3.2.2.1 Energy

The energy produced by humans is made by the degradation of energy substrates (carbohydrates and lipids). The oxydation of these substrates creates energy but also wastes energy. If we measure O2 consumption and CO2 production, this allows us to calculate energy expenditure and energy consumption.

##### *1.3.2.2.1.1 Respiratory quotient* $[QR]$

The carbohydrate/lipid consumption ratio is not the same at rest and effort. Therefore, we must use the notion of $QR$. The $QR$ is the ratio of the volume of exhaled CO2 (VCO2) divided by the inspired volume of O2 (VO2) and it indicates which macronutrients have been metabolized.

$$QR = \frac{VCO2}{VO2}$$

A $QR$ at 0.7, indicates that lipids are metabolized for an energy equivalent of 19.6 kJ (kiloJoules). A $QR$ at 1, indicates that carbohydrate are metabolized for an energy equivalent of 21.1 kJ. When the $QR$ value is between 0.7 and 1, a mixture of carbohydrates and lipids are metabolized. Therefore, when the anaerobic threshold is reached, the $QR$ tends to a value of 1.

##### *1.3.2.2.1.2 Energy cost (CE) and running economy (RE)*

Thus, by being equipped with an apparatus capable of measuring respiratory gas exchanges (using a mask), we can calculate the cost of running. But we have to choose a low running speed so as to stay below the anaerobic threshold, which induces an energy production with anaerobic metabolism.

The energy cost (CE) characterizes the energy consumption (aerobic and anaerobic metabolism) when producing a certain work. It is the energy expenditure per unit of body weight and per unit of distance traveled $(\mathrm{ml\,O2} \times \mathrm{kg}^{-1} \times \mathrm{km}^{-1})$ and can be related to a measure of the efficiency of the running. The energy is not measured directly in J (Joule), but the energy cost is measured indirectly by calorimetry by measuring the volume of oxygen consumed per unit of body weight and per unit of distance traveled $(\mathrm{ml\,O2} \times \mathrm{kg}^{-1} \times \mathrm{km}^{-1})$. This volume allows for the empirical approximation of the amount of energy consumed according to, among other things, the metabolism of the substrates and the associated $QR$. It is obtained by dividing the volume of oxygen consumed by the mass of the rider and his speed of displacement [31].

$$CE = \frac{VO2\ (ml\ O2/min)}{Masse(kg) \times Vitesse(\frac{km}{min})} = \frac{ml\ O2}{kg \times km}$$

Running Economy (RE) represents the oxygen consumption (VO2) (extrapolation of energy consumption at a given speed). It is also expressed in $\mathrm{ml\ O2} \times \mathrm{kg}^{-1} \times \mathrm{km}^{-1}$ at a certain speed. It looks at the ability of an individual to move efficiently on the energetic aspect[32]. In other words, it represents the energy cost in an aerobic metabolism. Runners with good economy use less oxygen than runners with poor economy at the same steady-state speed [33]. The running economy is calculated by the equation above.

The steady-state oxygen consumption ($VO_2$) at a given running velocity, which is often referred to as running economy (RE), reflects the energy demand of running at a constant submaximal speed [34] [35] [36].

The other necessary condition for the supply of energy comes from oxidative phosphorylation, e.g., 50–80 % or 60–90 % de la VO2max [35]. In more intense exercises (i.e., above the threshold of accumulation of blood lactate), some of the energy supplied comes from anaerobic glycolysis; resulting in an underestimation of CE [37]. The speeds of 8 and 10 km / h for women and 10 and 12 km / h for men were chosen because they are part of the standard speeds used to measure the racing economy and correspond to sub-threshold speeds for the runners we had included.

In subjects with the same VO2max value, energy cost (CE) has often been described as the most important factor influencing aerobic performance (with endurance) [36] [35]. So, Kearney et Van Handel [38] showed a variability of performances of the order of 15 to 20% in athletes of the same VO2max, explained by an inter-individual variability of the same order. Conversely, for the same trained subject, CE variability is lower when the measure is repeated from one day to the next (coefficient of variation of 1.6%, 1.8% or 4.6% [39] [40] [41] [42].

## 1.4 Objectives

This is the first study that explores the comparison of two fatigue protocols (Isokinetic vs Heel-Raise) of flexor ankle muscles with two different outcome measures (MVC and running economy) of such fatigue. For the time being, available clinical evaluations are only done in static or running mode, but without pre-fatigue considerations.

Thus, we needed to answer the two following questions:

1. Which values of running economy (RE) and maximum voluntary contraction (MVC) do we obtain after the two fatigue protocols of the ankle flexor muscles?
2. Do the two fatigue protocols induce the same worsening of running economy (RE) and maximum voluntary contraction (MVC) values?

In addition, the ultimate clinical goal of our study will be to validate a clinical protocol taking into account a pre-fatigue of the ankle flexor muscles in order to apply it to the context of running injury rate reduction in runners.

For clinicians, it would be extremely interesting to get reliable MVC and running related parameter through the Heel-Raise induced fatigue protocol for the following main practical reasons:

- Simple
- Fast
- Cheap

We would then be able to offer a screening program to patient who wants to know their injury exposure while running. High-risk patients could then follow a preventive strengthening program in order to reduce their injury rate.

## 1.5 Hypothesis

It was assumed that both fatigue protocols will result:

a) in a decrease in force generation or muscle action.
b) in MVIC value decrease and RE value increase.

The potential discrepancies between manual (HHD) and functional (treadmill) fatigue assessments and the potential differences between clinical (Heel-Raise) and isokinetic fatigue protocols may provide us with valuable data in order to help clinicians in preventing fatigue related injuries by runners.

# 2 Methodology

## 2.1 Subjects

Eighteen runners completed the study. All participants were healthy and pain-free during the testing period, had no history of musculoskeletal dysfunction or injuries of the lower limbs in the two months preceding testing.

| Subjects | Gender | BW | Height | Age |
|---|---|---|---|---|
| 1 | M | 62.8 | 178 | 44 |
| 7 | M | 91.5 | 190.5 | 27 |
| 8 | M | 85.8 | 194.5 | 23 |
| 9 | M | 81 | 185 | 40 |
| 10 | M | 78 | 180 | 35 |
| 12 | M | 58.5 | 174 | 27 |
| 13 | M | 81.2 | 179 | 37 |
| 14 | M | 72.5 | 171 | 23 |
| 15 | M | 67 | 170.5 | 24 |
| 16 | M | 74.6 | 181 | 24 |
| 2 | F | 56.2 | 162.5 | 23 |
| 3 | F | 71 | 166.5 | 24 |
| 4 | F | 68 | 178 | 27 |
| 5 | F | 53 | 162 | 23 |
| 6 | F | 79.5 | 175 | 28 |
| 11 | F | 51 | 165 | - |
| 17 | F | 68.1 | 163 | 21 |
| 18 | F | 58 | 169 | 31 |
| **AVERAGE** | | **69.9** | **174.7** | **28.3** |
| STDEV | | 11.7 | 9.5 | 6.8 |

**Table 1: Biometric parameters of the subjects**

The cohort used for the study presented the following characteristics (Table 1):

- Gender: 8 Females and 10 Men
- Mean age: 28.3 ± 6.8 years
- Mean body mass: 69.9 ± 11.7 kg
- Mean height: 174.7 ± 9.5 cm

The participants involved in the study practiced physical activities from moderate to vigorous level, were healthy and without known cardiovascular or metabolic comorbidities.

Although the study did not require prolonged effort at high cardiovascular intensity, we ensured the following elements:

a) The subjects completed the PAR-Q questionnaire (physical activity readiness questionnaire).
b) The questionnaire was completed by a history of cardiovascular risk factors (FRCV, ie smoking, diabetes, hypertension, hypercholesterolemia, positive family history by person <50 years of age).
c) Measurement of blood pressure and cardiovascular auscultation.

The inclusion criteria to participate to the study are listed below:

1) Informed Consent as documented by signature (See Appendix: Informed Consent Form).
2) Physically active subjects, that was a minimum of 5x30 min of moderate physical activity per week.
3) Prior experience with treadmill running.
4) Minimal ankle total range of motion of 60 degrees.

The exclusion criteria were the following:

1) Injury in lower limbs in previous two months.
2) Positive response to one of the PAR-Q questions, i.e. physical activity readiness questionnaire.
3) diabetes.
4) high blood pressure insufficiently treated or under investigation.
5) The presence of more than 1 FRCV.
6) Abnormal heart sounds or high blood pressure detected to the measurement.
7) Taking heart rate modifying medications such as beta blockers, calcium antagonists or beta2 inhaled stimulants within 12 hours prior to the study tests. Note that a person who occasionally took an inhaled stimulant beta2 has been allowed to participate if she or he meets the time limit.
8) Taking medications that is known to affect muscle strength (systemic corticosteroids).

Prior to the experiment, participants were familiarized with the purpose and significance of the study and safety measures regarding the experimental set-up. Informed consent was obtained from all participants. The study was accepted by the cantonal ethics committee from Geneva (project n° 2016-01752). Additionally, the ethical guidelines followed by the investigators conformed to the recommendations of the Declaration of Helsinki about human investigations.

## 2.2 Experimental protocol

The two protocols sessions were organized and separated by two days. This period was consistent across participants. Participants were asked to refrain from strenuous activity between the two protocols days.

The order of protocol was randomized by sequential numbering. Only half of the subjects performed the Heel-Raise fatigue protocol on day 1. The other half started with isokinetic apparatus fatigue protocol during day 1. But for readiness simplification, the document was written as if all the subjects started with the Heel-Raise fatigue protocol on day 1 and the isokinetic apparatus on day 2.

### 2.2.1 Program Day 1

The program of day 1 included 5 steps that are presented below:

1. Pre-fatigue treadmill running with recording of qualitative parameters (each subject was equipped with a mask to calculate the running economy (RE) by analyzing the inspired and exhaled air). The running economy (RE) was measured at two speeds, 8 and 10 km / h for women and 10 and 12 km / h for men.

2. Pre-fatigue measurement of the ankle flexor muscles was using a HHD (Hand-Held-Dynamoter). Strength of maximal voluntary contractions (MVC) was recorded with the HHD. We tested first the left flexor ankle muscles and then the right.
   For the HHD test, subjects were seated using the same arrangement as on the Biodex isokinetic machine. The zero position was those with the legs dangling with a knee flexion of 90°. The dynamometer was held against a wall. The height of the seat was a standard of superior quality. The subjects were responsible for holding the cuffs of the seat so that it was not from the back. Subjects were advised not to use their hands and arms to push themselves down during the test and were then asked to perform sub-maximal contraction with one leg in maximum extension in order to familiarize themselves with the apparatus and to warm up. The device was located under the metatarsal bones 1 to 5. After a minute of rest, the subject performed three maximum contractions with the encouragement of the tester. Between each contraction the subject had a minimum rest period of 10 seconds. Data obtained with the hand-held dynamometer were recorded in Newtons (N); the peak value and the average of the three trials were used for analysis. The HHD recorded the strength of MVC. After recording the left leg, we did the same think with the right leg [43 44 29].
3. Fatigue protocol with a single-leg Heel-Raise. The order of use between left and right leg was randomised. Ankle flexor muscles fatigue was caused by simple protocol of single-leg Heel-Raise. This standard protocol measures the endurance of the ankle flexor muscles [45]. The frequency of the Heel-Raise was one every 2 seconds (0.5Hz or 30 per minute) and was determined by a metronome with 60 beats per minutes. The subject was standing bare foot; leg and foot were completely exposed. The knee was fully extended during the protocol. The subject put its arms at shoulder level and they were full extended. Only the fingertips touched the wall and were used for the balance. In 1995, Lunsford and Perry decided that for a normal Heel-Raise, you must have more than 50% of the maximal Heel-Raise height [25]. The 50% criterion was chosen because investigators who used the 50% fatigue criterion reported that this value corresponded to short-lived fatigue effects [46].

   We stopped counting the number of Heel-Raise if there were 3 consecutive Heel-Raises with less than 50% of the maximal height [47].

   The protocol was also considered as terminated [47 45]:

   - when the subject used the upper limbs
   - if there was a movement of the body
   - if he used his hand for upward propulsion
   - if the subject did an excessive forward truck (20°) or knee flexion (>25°) and
   - when the subject was unable to continue due to fatigue or if he used compensations muscles

   The subject performed first 3-5 Heel-Raises to ensure that he performs the test correctly. There were 60 seconds of rest before the beginning of the fatigue protocol.
   It took two test controllers, one who was in charge of counting the number of Heel-Raise and the other looked that the subject did not use compensation strategies.

Then the subject rested again 60 seconds before we fatigued the other leg. During the protocol, the controller encouraged the subject to do a maximum of Heel-Raises. For female and male, 25 Heel-Raises repetitions are considered as normal [25].

4. Post-fatigue measurement of the ankle flexor muscles using a HHD. Strength of maximal voluntary contractions (MVC) was recorded with the HHD. We were testing first the left flexor ankle muscles and then the right flexor ankle muscle. The HHD measuring procedure was exactly the same as in the recording of pre-fatigue.
5. Post-fatigue treadmill running with recording of qualitative parameters (each subject was equipped with a mask to calculate the running economy (RE) by analyzing the inspired and exhaled air). The RE was measured at two speeds, 8 and 10 km/h for girls and 10 and 12 km/h for men. The treadmill running measuring procedure was exactly the same as in the recording of pre-fatigue.

### 2.2.2 Program Day 2

The program of day 2 included 4 steps that are explained below:

1. Following a brief warm-up (15 minutes of ergometric cycling at a heart rate of 60%-80% of the maximum frequency. According to Haskell and Fox [48], 1970, an approximation of the maximum heart rate is obtained using the 220-age formula). We conducted a new analysis of the ankle flexor muscles using a HHD. The HHD measuring procedure was exactly the same as the first day test.
2. Fatigue protocol of the ankle flexor muscles with an isokinetic apparatus (Cybex with the Humac Norm Software from Hospital La Tour, Meyrin-Geneva). The order of use between left and right leg was randomised. The fatigue protocol consisted in an alternation of the maximal isokinetic contractions in extension and flexion. This as many times as possible, i.e., until the torque for three consecutive contractions sets decreased below 50% MVC for ankle flexor muscles. With each subject, the isokinetic dynamometer was calibrated. The ankle was set in a 0° dorsiflexion, with back inclination of 70°, and knee flexion of 30–45°. The foot was in full contact with the foot plate without inhibiting ankle range of motion. A support was placed under the distal thigh to support the limb weight and allowed for relaxed support at the knee. Participant movement was restricted to limit the effects of assistor movements with straps placed over the forefoot, ankle, distal thigh, waist and chest. The other foot was rested on a support to limit twisting of the body upon contraction; this was placed to the end of the dynamometer bed in front of the motor unit. After recording the first isokinetic fatigue we did the same think with the opposite leg. Encouragement was given throughout the exercise to produce maximal effort in each contraction [49] [23] [50].
3. Post-fatigue measurement of the ankle flexor muscles using a HHD. The HHD measuring procedure was exactly the same as in the recording of pre-fatigue.
4. Post-fatigue treadmill running with recording exactly the same way as on Day 1.

# 3 Statistical Analysis

The study focused on whether there are significant differences in the distribution of the independent variables.

Then the nonparametric test Mann-Whitney U test was used for all the variables. The normal assumption could not be accepted due to our sample size of less than 20 subjects. Statistical significance has been accepted at $p < 0.05$.

Furthermore, it was assumed that:

1. All the observations from both groups are independent of each other.
2. The responses are ordinal (i.e., one can at least say, of any two observations, which is the greater).
3. Under the null hypothesis H0, the distributions of both populations are equal.
4. The alternative hypothesis H1 is distributions are not equal.

$H_0$: “The two samples have the same distribution", in other words fatigue protocols had no influence on the force produced (MVC) or no influence on the economy of running (CE).

$H_1$: "The two samples don’t have the same distribution", in other words fatigue protocols had an influence on the force produced (MVC) or an influence on the economy of running (CE).

If the P-value is > 0.05, the hypothesis $H_0$ was not rejected.

If the P-value is < 0.05, the hypothesis $H_0$ was rejected.

# 4 Results

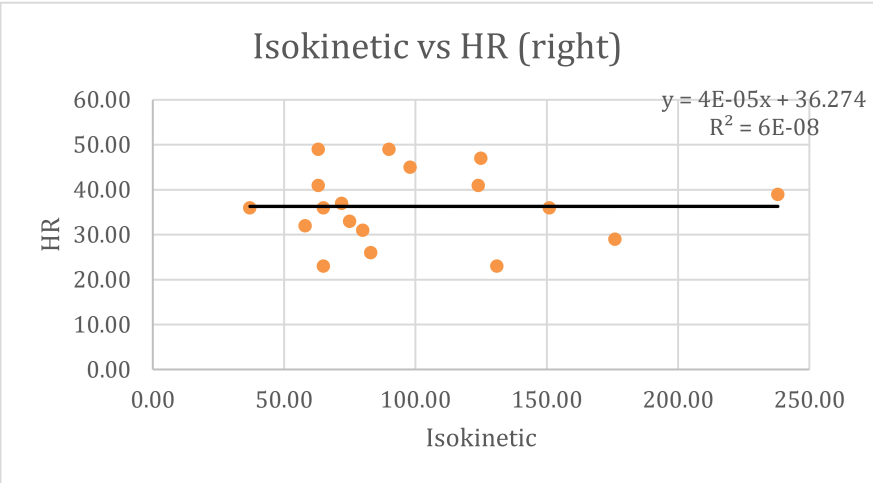
The results of the study are presented in the following sections.

## 4.1 Fatigue protocols

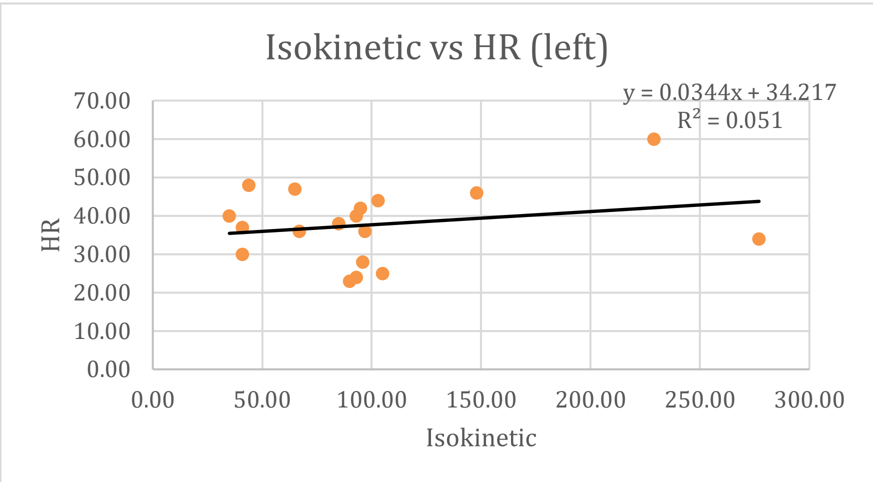
The results of fatigue protocols are summarized in the following tables and graphs.

| | Average repetition | STDV |
|---|---|---|
| HR repetition for the right leg | 36.3 | 8.2 |
| HR repetition for the left leg | 37.7 | 9.6 |
| Isokinetic repetition for the right leg | 99.7 | 50.1 |
| Isokinetic repetition for the left leg | 100.2 | 63.0 |

**Table 2: Average number of repetition of both fatigue protocols for men and women**




**Graph 1: Correlation of the number of repetitions between the two fatigue protocols for the right leg for men and women**




**Graph 2: Correlation of the number of repetitions between the two fatigue protocols for the left leg for men and women**

## 4.2 Values of Running Economy (RE) and maximum voluntary contraction (MVC) after the two fatigue protocols

### 4.2.1 Running Economy

The results of Running Economy (RE) are summarized in the following tables.

| | $\mathbf{ml\ O2 \times kg^{-1} \times km^{-1}}$ | **STDV** |
|---|---|---|
| Pre-fatigue protocol RE at the low speed for men and women | 179.0 | 18.0 |
| Pre-fatigue protocol RE at the high speed for men and women | 192.0 | 20.0 |

**Table 3: Running economy at low and high speed pre-fatigue protocol for men and women**

| | $\mathbf{ml\ O2 \times kg^{-1} \times km^{-1}}$ | **STDV** |
|---|---|---|
| RE of post HR protocol at the low speed for men and women | 182.5 | 21.2 |
| RE of post HR protocol at the high speed for men and women | 192.2 | 20.3 |

**Table 4: Running economy at low and high speed post Heel-Raise fatigue protocol for men and women**

| | $\mathbf{ml\ O2 \times kg^{-1} \times km^{-1}}$ | **STDV** |
|---|---|---|
| RE of post Isokinetic protocol at the low speed for men and women | 176.2 | 21.2 |
| RE of post Isokinetic protocol at the high speed for men and women | 182.7 | 19.2 |

**Table 5: Running economy at low and high speed post Isokinetic fatigue protocol for men and women**

### 4.2.2 Values of MVC for pre and post fatigue protocol

The results of the pre and post-fatigue protocol for the MVC values are summarized in the following tables and graphs.

| | Newton (N) | STDV |
|---|---|---|
| Maximum value of MVC for the right leg pre-fatigue protocol for men and women | 1129.4 | 181.3 |
| Average value of MVC for the right leg pre-fatigue protocol for men and women | 1075.0 | 181.1 |
| Maximum value of MVC for the left leg pre-fatigue protocol for men and women | 1158.7 | 180.1 |
| Average value of MVC for the left leg pre-fatigue protocol for men and women | 1088.2 | 162.7 |

**Table 6: Values of MVC pre-fatigue protocol for men and women**

| | Newton (N) | STDV |
|---|---|---|
| Maximum value of MVC for the right leg post HR fatigue protocol for men and women | 1112.1 | 205.2 |
| Average value of MVC for the right leg post HR fatigue protocol for men and women | 1052.2 | 214.5 |
| Maximum value of MVC for the left leg post HR fatigue protocol for men and women | 1108.9 | 202.6 |
| Average value of MVC for the left leg post HR fatigue protocol for men and women | 1075.3 | 210.7 |

**Table 7: Values of MVC post Heel-Raise fatigue protocol for men and women**

| | Newton (N) | STDV |
|---|---|---|
| Maximum value of MVC for the right leg post Isokinetic fatigue protocol for men and women | 1144.0 | 203.6 |
| Average value of MVC for the right leg post Isokinetic fatigue protocol for men and women | 1098.6 | 212.9 |
| Maximum value of MVC for the left leg post Isokinetic fatigue protocol for men and women | 1044.4 | 172.8 |
| Average value of MVC for the left leg post Isokinetic protocol for men and women | 1070.8 | 178.3 |

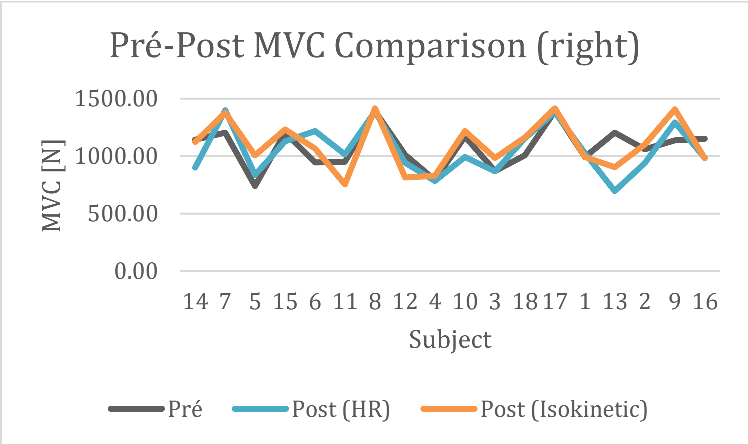
**Table 8: Values of MVC post Isokinetic fatigue protocol for men and women**

| | % |
|---|---|
| Decrease in % between pre and post HR fatigue protocol for maximum value of MVC for the right leg | -0.7 |
| Decrease in % between pre and post HR fatigue protocol for average value of MVC for the right leg | -1.3 |
| Decrease in % between pre and post HR fatigue protocol for maximum value of MVC for the left leg | -3.4 |
| Decrease in % between pre and post HR fatigue protocol for average value of MVC for the left leg | -1.3 |

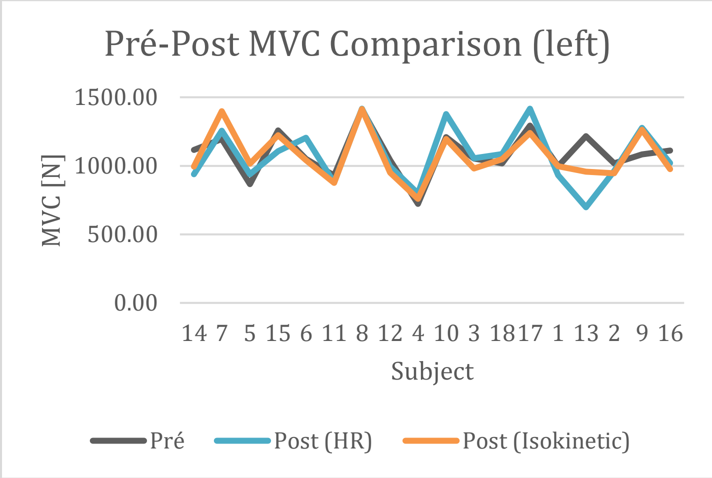
**Table 9: decrease in % between pre and post Heel-Raise fatigue protocol**

| | % |
|---|---|
| Decrease in % between pre and post Isokinetic fatigue protocol for maximum value of MVC for the right leg | 2.1 |
| Decrease in % between pre and post Isokinetic fatigue protocol for average value of MVC for the right leg | 2.9 |
| Decrease in % between pre and post Isokinetic fatigue protocol for maximum value of MVC for the left leg | -3.1 |
| Decrease in % between pre and post Isokinetic fatigue protocol for average value of MVC for the left leg | -1.3 |

**Table 10: decrease in % between pre and post Isokinetic fatigue protocol**




**Graph 3: Difference between each subject pre and post fatigue protocol on the values of MVC for left leg**




**Graph 4: Difference between each subject pre and post fatigue protocol on the values of MVC for left leg**

## 4.3 Number of repetition for fatigue protocols, maximum voluntary contraction (MVC) and running economy (RE) between women and men after the two fatigue protocols

The results of the number of repetition for both fatigue protocols, MVC and running economy (RE) between women and men are summarized in the following tables (tables 11, 12, 13, 14, 15, 16, 17 and graphs 7, 8, 9, 10):

### 4.3.1 Running Economy

The results of RE between men and women are summarized in the following tables (tables 11, 12).

| | **Women** ($\mathbf{ml\ O2\ \times\ kg^{-1} \times\ km^{-1}}$) | **Men** ($\mathbf{ml\ O2\ \times\ kg^{-1} \times\ km^{-1}}$) | **Difference between women and men** |
|---|---|---|---|
| Pre-fatigue protocol RE at the low speed | 180.0 | 180.0 | 0.0 |
| Pre-fatigue protocol RE at the high speed | 190.0 | 200.0 | 10.0 |

**Table 11: Difference of running economy at low and high speed pre-fatigue protocol between women and men.**

| | Women $(\text{ml O2} \times \text{kg}^{-1} \times \text{km}^{-1})$ | Men $(\text{ml O2} \times \text{kg}^{-1} \times \text{km}^{-1})$ | Difference between women and men |
|---|---|---|---|
| RE of post HR fatigue protocol at the low speed | 180.0 | 180.0 | 0.0 |
| RE of post HR fatigue protocol at the high speed | 190.0 | 190.0 | 0.0 |
| RE of post Isokinetic fatigue protocol at the low speed for men and women | 180.0 | 180.0 | 0.0 |
| RE of post Isokinetic fatigue protocol at the high speed for men and women | 180.0 | 180.0 | 0.0 |

**Table 12: Difference of running economy at low and high speed post Heel-Raise and Isokinetic fatigue protocols between men and women**

### 4.3.2 Number of repetition for Heel-Raise and Isokinetic fatigue protocols

The number of repetitions for both fatigue protocols between women and men are summarized in the following table (tableau 13).

| | Women | Men | Difference between women and men |
|---|---|---|---|
| HR repetition for the right leg | 37.8 | 35.1 | -2.7 |
| HR repetition for the left leg | 37.5 | 37.8 | 0.3 |
| Isokinetic repetition for the right leg | 92.0 | 105.8 | 13.8 |
| Isokinetic repetition for the left leg | 105.8 | 99.8 | -6.0 |

**Table 13: Difference of average number of repetition of both fatigue protocol for men and women**

### 4.3.3 Difference of values of MVC for pre and post fatigue protocol between man and women

The values of MVC between women and men are summarized in the following tables (tables 14, 15, 16 and 17). The graphs 7 and 8 for women and 9 and 10 for men show in a visual way the values between men and women.

| | Women - Newton (N) | Men - Newton (N) | Difference between women and men |
|---|---|---|---|
| Maximum value of MVC for the right leg pre-fatigue protocol | 1009.6 | 1225.3 | 215.7 |
| Average value of MVC for the right leg pre-fatigue protocol | 968.4 | 1160.3 | 191.9 |
| Maximum value of MVC for the left leg pre-fatigue protocol | 1051.1 | 1244.8 | 193.7 |
| Average value of MVC for the left leg pre-fatigue protocol | 993.7 | 1163.9 | 170.2 |

**Table 14: Difference of values of MVC pre fatigue protocol for men and women**

| | Women - Newton (N) | Men - Newton (N) | Difference between women and men |
|---|---|---|---|
| Maximum value of MVC for the right leg post HR fatigue protocol | 1075.8 | 1141.2 | 65.4 |
| Average value of MVC for the right leg post HR fatigue protocol | 1024.1 | 1074.6 | 50.5 |
| Maximum value of MVC for the left leg post HR fatigue protocol | 1070.6 | 1139.6 | 69.0 |
| Average value of MVC for the left leg post HR fatigue protocol | 1042.3 | 1101.7 | 59.4 |

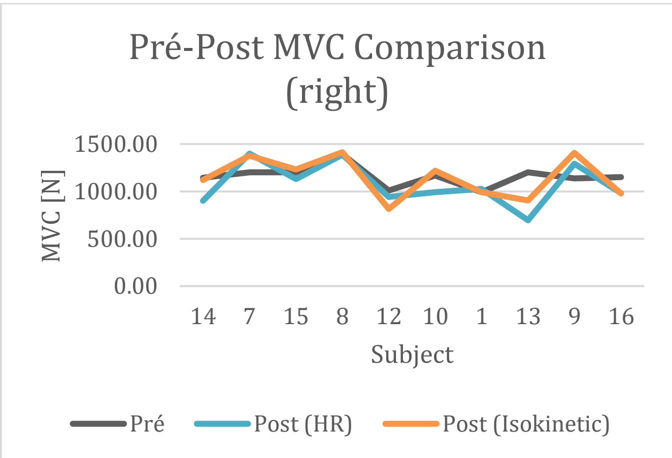
**Table 15: Difference of values of MVC post Heel-Raise fatigue protocol between men and women**

| | Women - Newton (N) | Men - Newton (N) | Difference between women and men |
|---|---|---|---|
| Maximum value of MVC for the right leg post Isokinetic fatigue protocol | 1089.6 | 1187.5 | 97.9 |
| Average value of MVC for the right leg post Isokinetic fatigue protocol | 1039.2 | 1146.1 | 106.9 |
| Maximum value of MVC for the left leg post Isokinetic fatigue protocol | 1044.4 | 1167.0 | 122.6 |
| Average value of MVC for the left leg post Isokinetic protocol | 988.3 | 1136.7 | 148.4 |

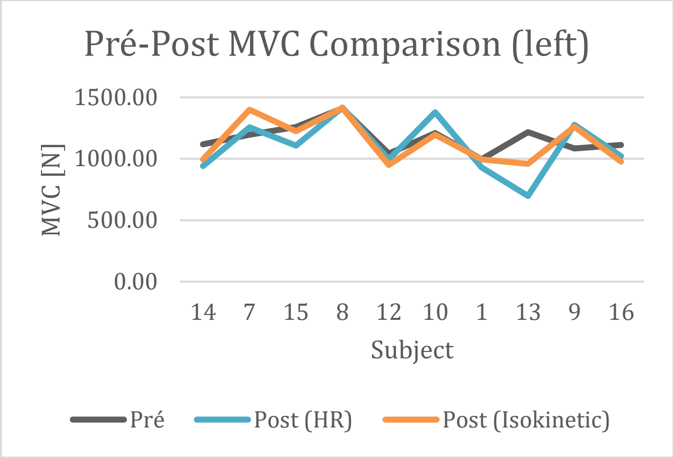
**Table 16: Difference of values of MVC post Isokinetic fatigue protocol between men and women**

| | % Women | % Men |
|---|---|---|
| Decrease in % between pre and post HR fatigue protocol for maximum value of MVC for the right leg | 6.9 | -6.7 |
| Decrease in %between pre and post HR fatigue protocol for average value of MVC for the right leg | 6.3 | -7.3 |
| Decrease in % between pre and post HR fatigue protocol for maximum value of MVC for the left leg | 2.4 | -7.9 |
| Decrease in % between pre and post HR fatigue protocol for average value of MVC for the left leg | 4.9 | -5.2 |
| Decrease in % between pre and post Isokinetic fatigue protocol for maximum value of MVC for the right leg | 8.8 | -3.2 |
| Decrease in % between pre and post Isokinetic fatigue protocol for average value of MVC for the right leg | 8.4 | -1.5 |
| Decrease in % between pre and post Isokinetic fatigue protocol for maximum value of MVC for the left leg | 0.3 | -5.9 |
| Decrease in % between pre and post Isokinetic fatigue protocol for average value of MVC for the left leg | 0.1 | -2.3 |

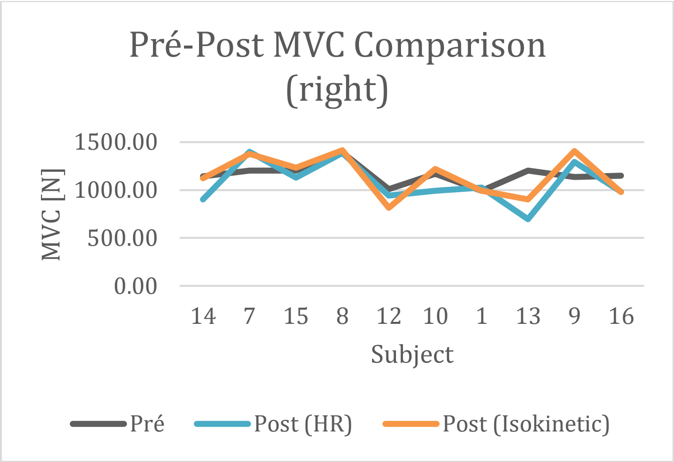
**Table 17: decrease in % between pre and post Isokinetic fatigue protocol and Heel-Raise fatigue test between men and women**



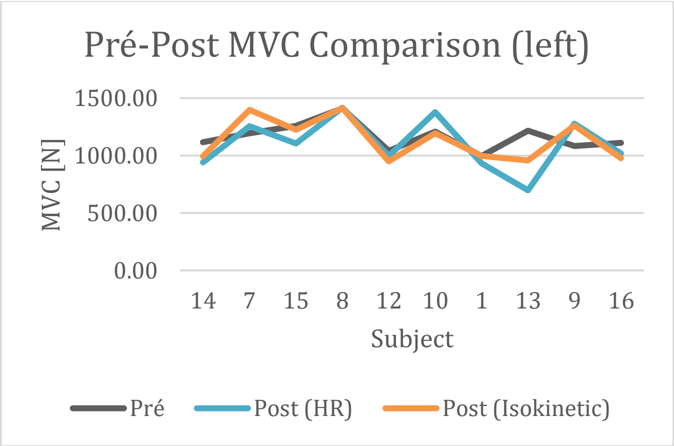

**Graph 7: Difference of the value of MVC pre and post fatigue protocol for the right leg for women**




**Graph 8: Difference of the value of MVC pre and post fatigue protocol for the left leg for women**




**Graph 9: Difference of the value of MVC pre and post fatigue protocol for the right leg for men**




**Graph 10: Difference of the value of MVC pre and post fatigue protocol for the left leg for men**

# 5 Discussion

Our study explores the comparison of a double fatigue protocols (Isokinetic vs Heel-Raise) of flexor ankle muscles with a double outcome assessment (MVC and running economy) of such fatigue. The aim of our study was to compare the effect of functional Heel-Raise induced fatigue versus isokinetic induced fatigue protocols on MVC and on running economy.

## 5.1 Fatigue protocols

In the table 2, we see the value of average number of repetition of both fatigue protocols. In the graphs 1 and 2 we have the correlation of the number of repetition of both fatigue protocols.

For the Heel-Raise fatigue protocol, the average repetition number was 36.3 ± 8.2 for the right leg and 37.7 ± 9.6 for the left leg (table 2). The number of repetitions was not affected by the gender, weight, height or BMI.

Lunsford and al., 1995 [25], decided that the reference value of the number of repetitions was 25 with a frequency of one Heel-Raise every two seconds to be in the standard. In our study, we found values of 36.3 ± 8.2 repetitions for the right leg and 37.7 ± 9.6 repetitions for the left. Our subjects were therefore well above the norm. Only three subjects performed fewer than 25 repetitions.

A study by Bennett and al., 2012 [45], conducted on 77 cross-country college athletes (44 males, 33 women) did not show an increased risk of exercise-related leg pain in the follow season for subjects who did <25 repetitions.

The average repetition rate for the isokinetic fatigue protocol was 99.7 ± 50.1 for the right leg and 100.2 ± 63.0 for the left leg (table 2). The number of repetitions was not affected by the gender, weight, height, or BMI.

We found values of the number of contractions with isokinetic device of 100.2 ± 63.0 for left leg and 99.7 ± 50.1 for right leg. A study by Brouner and al., 2014 [23], showed a number of contractions in 14 healthy men with the dominant leg of 139 ± 31. We observed a 28% decrease in the number of repetitions in our study.

In the Heel-Raise fatigue protocol, we were above the expected values whereas in the isokinetic fatigue protocol we were below the expected values.

We did not see any correlation between the number of Heel-Raise and the number of repeats with the isokinetic apparatus (graphs 1).

A hypothesis for this results was that some subjects did not perform a maximal isokinetic contraction in extension and flexion during fatigue protocols during the first contractions, which led to an increase in the number of replication. We can imagine that some subjects used means of compensation during the fatigue protocol with the isokinetic apparatus (wrist and arm).

Moreover, the Heel-Raise fatigue protocol requires a concentric and eccentric muscular work whereas the isokinetic protocol requires only a concentric muscular work. Strong and enduring subjects in concentric muscular contraction will not necessarily be strong and enduring for concentric and eccentric muscular work.

## 5.2 Which values of the running economy (RE) and maximum voluntary contraction (MVC) do we obtain after the two fatigue protocols of ankle flexor muscles?

### 5.2.1 Running Economy

We found a p-value > 0.05 (no significant difference) for running economy pre and post fatigue protocol at low and high speed, so we couldn't reject the hypothesis $H_0$ (the two samples have the same distribution) (tables 3, 4, 5).

However, when we observe the values, we could notice an increase of running economy at low speed after the Heel-Raise fatigue protocol but a decrease after the isokinetic fatigue protocol. At high speed we can notice a slight increase of running economy after the Heel-Raise fatigue and a decrease after the isokinetic fatigue protocol.

Abbott and al. in 1952 showed that concentric muscle contractions during propulsion are metabolically more expensive than eccentric muscle contractions during braking [51]. By downhill running, we perform less expensive negative work because the muscles lengthen while inducing tension [52]. By uphill running, it is the opposite, the muscles shorten likely while having tension [53]. During uphill running they consume more energy, resulting in higher metabolic fatigue [17].

### 5.2.2 Values of MVC for pre and post fatigue protocol

We found a p > 0.05 (no significant difference) on the value of the MVC for both fatigue protocols pre and post fatigue protocols (tables 6, 7, 8, 9, 10 and graphs 3 and 4).

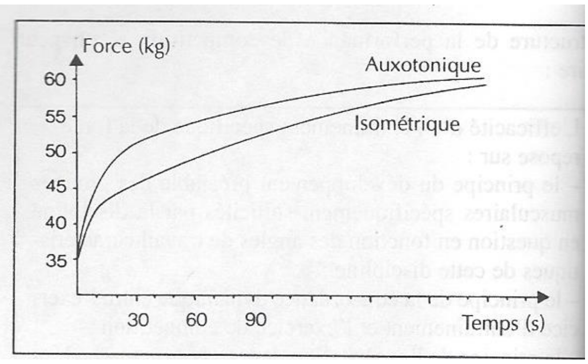
### 5.2.3 Discussion for the value of the MVC pre and post-fatigue protocol

Four possibilities might have explain that they were no significant pre and post-fatigue differences between the two fatigue protocols on the MVC value.

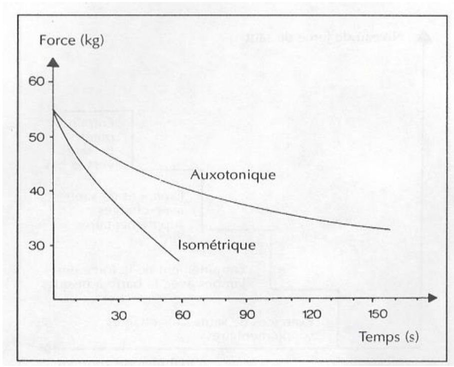
a) First, the cybex machine and the Heel Raise were dynamic fatigue protocols. The evaluation of MVC with HHD was performed using isometric position, which may not correspond to a dynamic evaluation of muscle fatigue.
   Fourchet and al. in 2012 [54] examined the effects of a 5h hillly running on the ankle plantar flexor and dorsal flexor force and fatigability. In particular, this study tested for ankle plantar flexor (PF) and ankle dorsal flexor (DF) the maximal voluntary isometric contraction strength, the maximal voluntary isokinetic contraction strength and the fatigue resistance tests (percent decrement score) before and after the run the 5-h hilly running. The results showed a decrease in PF pre and post run of voluntary maximal isometric contraction (-17 ± 6.2%), but not a significant decrease in DF (-7.9 ± 6.2%). The maximum voluntary isokinetic contraction force and fatigue resistance remained unchanged for DF and PF.
   In this study, our fatigue protocols were used as a fatigue test. It might have been relevant for our study to measure fatigue resistance using our Heel-Raise and isokinetics protocols as a fatigue test while keeping the isokinetic fatigue protocol. This will make possible to avoid the bias of a fatigue measurement in static while the fatigue protocols are dynamic exercises. Moreover, this study shows that even after 5-h hilly running we do not see any change in the maximal voluntary isokinetic contraction and fatigue resistance, there is only a decrease in the voluntary maximum isometric significant contraction. It is also difficult to imagine that our two

dynamic fatigue protocols induce a significant decrease in force on a static evaluation of the force even if it is difficult to correlate the two studies.

b) The immediate recovery after stopping the effort [55]. The fact that there was a time lag between the end of fatigue protocols and the measurement of MVC allowed recovery of non-negligible muscle strength (graph 5 [56] ).Our two fatigue protocols were short-term and high-intensity exercises. Short-term and high-intensity exercises were exercises where the energy production was anaerobic alactic, lactic anaerobic and anaerobic-aerobic. Recovery of organic and cellular functions occurred after the effort had ceased.




**Graph 5: Recovery curve in dynamic and static work (reproduced from Stull et Clarke 1971, 137)**




**Graph 6: Fatigue curve in dynamic and static work (reproduced from Stull et Clarke 1971, 136)**

Moreover, our fatigue protocols were dynamic exercises that cause a rapid decrease in strength, but still less rapid than a static (isometric) exercise (graph 6 [56] ). In the regeneration phase, there is a very rapid recovery of the force followed by a slower recovery. The recovery of the force is faster for dynamic exercises than static. During short-term efforts, as in those involving force-velocity with maximum intensity, there is a very marked decrease in ATP reserves in the muscles involved. The resynthesis of the ATP thus used is carried out from the creatine-phosphate stores. The regeneration of ATP (at rest) requires between 1 and 3 min.

In further studies there may be beneficial that after having tired one leg in the fatigue protocols to directly measure the MVC and then fatigue the other leg followed by the measurement of the MVC. This will reduce the bias in the recovery of muscle strength between the end of fatigue protocols and the measurement of MVC. In our study we randomized the left and right leg. The results did not give a significant difference between the left and right leg.

c) The fatigue protocols may also have resulted in a muscle warm-up effect instead of fatiguing effect. For this reason, we could even observe by some subjects, a trend of improvement in MVC post fatigue protocol. As a reminder of the warm-up: all the measures allowing to obtain an optimal state of psychological and motor preparation (kinesesthesia) before a training or a competition, and which at the same time play a role of prevention of the lesions [57]. In other words, the warm-up is to raise the athlete's level to allow him to reach his best potential at the end of it.

Another rationale underlying these findings is the so-called Post-Activation Potentiation (PAP) principle defined by Robbins as a phenomenon by which the force exerted by a muscle increases, due its previous contraction [58].

Empirically he coaches and S&C coaches noticed that their athletes who conducted preludes with heavy loads can produce more strength or power than usual. The

PAP claims that the contraction of a muscle influences subsequent muscle contractions. Short muscular contractions with a high load that does not tire the muscle improves muscle performance. In other words, excitation of the nervous system makes an increase in muscle contraction by heavy load conditioning. The PAP is induced by maximum voluntary loads with amplitudes that can be maximum or partial. This phenomenon can also be present under sub maximum loads.

The effects of the potentiation must be greater than the effects of the fatigue induced so that a surplus of force may be obtained. When this is no longer the case, we have reached an intensity threshold beyond which the potentiation has no effect. A good warm-up should have the best possible PAP / Fatigue ratio. The relationship between PAP and fatigue is dependent on many parameters. The intensity, type and volume of loads and the rest time before the muscle contractions that follow. The PAP is maximal immediately after the stimulus and will reduce 10-15 minutes after the muscle has been triggered [59 60].

The application of the PAP must be personalized, therefore the exercises must be adapted to the sport activities performed by the athlete [61].

The characteristics of the subject have a considerable influence in the PAP phenomena but it is the muscular characteristics which has the most particular one. Type II muscle fibers are more capable of potentiation than Type I fibers. Athletes with a better Fiber II / Fiber I ratio (sprinter, jumper, weight lifter) will have a better effect of the PAP phenomenon. PAP is also more beneficial in muscles with short contractions [62 63 64 65 66 67 68].

Two hypotheses explaining the PAP phenomena:

1. The most cited mechanism that is responsible for PAP is the phosphorylation of the myosin light chains used during contraction that increases the sensitivity of actin-myosin to $Ca2^{+}$ released by the sarcoplasmic reticulum [69 70]. This results in greater force generation of protein bridges during subsequent contractions [71].
2. Muscle contractions may increase the potential for excitement in the spinal cord resulting in increased motor unit recruitment. This excitation could last several minutes, which would increase the post-synaptic potentials which leads to the increase of the generation of force [72].

The use of PAP may increase the strength, power and speed qualities in the terminal phase of physical rehabilitation in sport as well as increase the qualities of an athlete.

The effect of PAP has certainly been able to play a role in the no significant pre and post-fatigue differences for the two fatigue tests on the MVC value.

d) Finally, when the MVC was measured, the subjects were asked not to help themselves with their arms. Several subjects help by pushing with their back while having their arms outstretched. We did not ask the subject to position themselves in a supine position in order to avoid slippage when measuring the MVC with the HHD. Measurement of the MVC in dorsal supine position can be done with a restraining device placed above the shoulders as described in a study by Marmon and al. in 2013 [30]. Therefore, the value of the MVC might has been overestimated whether it is in pre and post test. In addition, subjects had no previous experience of measuring the MVC using a dynamometer. It was possible that during the measurement of the pre-fatigue MVC they did not grow to their maximum force and only during the second measurement they were pushing with their maximum force.

## 5.3 Do the two fatigue protocols induce the same worsening of running economy (RE) and maximum voluntary contraction (MVC) values?

We found no significant post-fatigue difference in MVC between the two fatigues protocols. Our depletion exercises induced a non-significant effect on fatigue of the plantar flexors, this without difference between the two protocols.

We found no significant post-fatigue difference in running economy between the two protocols. However, when we looked at the RE values, we observed the following differences in post fatigue between isokinetic and Heel-Raise protocol: a difference of 6.3 $\mathrm{ml\,O2} \times \mathrm{kg}^{-1} \times \mathrm{km}^{-1}$ at the low speed and 9.5 $\mathrm{ml\,O2} \times \mathrm{kg}^{-1} \times \mathrm{km}^{-1}$ at the high speed (see table 4 and 5). We also observed a slight difference in the MVC values between the two fatigue protocols (see table 9 and 10).

These small but no significant differences are beneficial for the purpose of finding a similarity between the two fatigue protocols.

## 5.4 Do we obtain similar values of the number of repetitions for fatigue protocols, maximum voluntary contraction (MVC) and running economy (RE) between women and men after the two fatigue protocols?

When we analyzed separately the men and the women gender we found some differences (tables 11, 12, 13, 14, 15, 16, 17 and graphs 7, 8, 9, 10).

### 5.4.1 Running Economy

When we analyzed men and women separately we found a $p > 0.05$ (no signifying difference) for both men and women on the value of running economy for both fatigue protocols (tables 11, 12).

However, when we compared the average values of running economy between men and women, we still observed a difference of 10.0 $\mathrm{ml\,O2} \times \mathrm{kg}^{-1} \times \mathrm{km}^{-1}$ measure of the pre-fatigue protocol energy cost at the high speed (Tables 11).

Daniels, J. and N. Daniels in 1992 [73] compared the running economy of elite male and elite female runners. The results showed that men are more economical than women at absolute running velocities, but when expressed in $\mathrm{ml\,O2} \times \mathrm{kg}^{-1} \times \mathrm{km}^{-1}$ there are no gender differences anymore. Also, when we matched men and women for equal VO2max and equal economy the men show a better aerobic profile.

### 5.4.2 Number of repetitions for Heel-Raise and Isokinetic fatigues protocols

We had no significant difference ($p > 0.05$) on the value of the number of repetitions of Heel-Raise and Isokinetic fatigue protocol between men and women (tableau 13).

Lunsford and al [25] also showed that gender have no influence on the number of repetitions of Heel-Raises. Lunsford and al explained this with the difference of body mass between man and women. We support that a protocol which is challenging the individual against their own body mass gives a more functional, relevant result. Since men subjects are 32 % heavier than the women subjects, the body mass difference can be seen as an equalizer. In our study, men weigh in average 16.2% more than women. The equality in the number of repetition, when doing standing Heel-Raise protocols between man and women could be explained by the fact that male can generate more force but are heavier.

The isokinetic fatigue protocol did not assure us that the patient pushed with all his strength at each repetition. One hypothesis was that in our study, men subjects did more sports than women subjects. They knew easier their maximum strength capability. Therefore, a man would have more tendency to make series close to the maximum levels while women were below their maximum level.

#### 5.4.3 Difference of values of MVC for pre and post fatigue protocol between man and women

When we analyzed men and women separately we found a $p > 0.05$ (no signifying difference) on the value of the MVC for the two fatigue protocols (tables 14, 15, 16, 17 and the graphs 7, 8, 9, 10). In other words, when we separately analyzed men and women we did not see significant differences on the values of the MVC pre and post fatigue protocol. In both cases there was no significant degradation of the force. However, we observed differences when we looked at the values (see 5.4.4).

#### 5.4.4 Discussion between difference women and men on the value of MVC.

A first observation that we could make was that in general men has more strength than women (tables 14, 15, 16 and graphs 7, 8, 9, 10). This was explained by the superior MVC values in pre and post fatigue protocol.

For a similar weight and similar training, a man will generally have more strength than the woman, this is explained by the fact that men produces more testosterone therefore they have more muscle tissue and less adipose tissue than the woman for a similar weight. A woman produces more estrogen than a man which leads to a higher percentage of adipose tissue and a smaller muscle mass. By women, the proportion of muscle tissue in the transverse section of the arm is 75.6% of that of the male, whereas the fatty tissue is almost double [74 75].

We showed a difference in the effect of post fatigue strength between men and women (Table 17 and graphs 7, 8 ,9, 10). We observed that by a woman there was an increase in strength after the two tests of fatigue for both leg (table 17). By men there was a decrease in strength after the two fatigue tests for both legs (table 17).

We considered that the difference in this result is not a gender problematic, but it is rather related to the number of hours of sports practiced per week. It turned out that in our study men subjects did more sports than women. For those who performed less sports, it could be assumed that the fatigue tests served as a warm-up (warm-up is supposed to bring all the functional capacities to a higher level [57 76] ) than fatigue protocols. This has resulted in an increase of post-fatigue MVC.

# 6 Limits of the study

The following limiting factors must be considered in our study:

- Inclusion criteria of our study had only subjects between 18 to 50 years old, sportively active and without neuromuscular problems or diseases.
- Limited size (18) of the subjects sampled.
- Measure of the MVC was depending of the test person.
- Subjects used means of compensations for MVC measurement.
- Dynamic fatigue protocols while the force measurement was static.
- Some subjects used means of compensation during the fatigue protocols.

# 7 Conclusion

Even though we could not achieve all our objectives and demonstrate the hypothesis, our study has made possible through the measurements of pre and post fatigue protocols with 18 subjects, to bring up important elements regarding the effects of the two fatigue protocols on force production and running economy.

Regarding the effects of the two fatigue protocols on force production and running economy, we noticed that our fatigue protocols do not fatigue as much as initially thought. Nevertheless, we observed some pre and post test differences on strength and running economy, mainly between men and women.

Several criteria explain our results. The main criteria are the phenomenon of PAP, the fact that the fatigue protocols have also resulted in a muscle warm-up effect instead of fatiguing, and that our fatigue protocols are dynamic exercises while the measurements of the MVC are static. But to a lesser extent, a fatigue protocol works only in concentric (isokinetic) while the other works in concentric and eccentric (Heel-Raise), the means of compensation used by the subjects during the measurement of the MVC as well that the fact that the muscles had an immediate recovery after stopping the effort.

If we wanted to reach our overall objective, which was to validate a simple, fast and cheap clinical protocol, taking into account a pre-fatigue of the ankle flexor muscles in order to decrease the injury rate by runners, it would be interesting to repeat the study with more participants and an expansion of the inclusion criteria. It would be interesting to measure force with an isokinetic dynamometer and a simple HHD in order to compare the static and dynamic force to see if we achieve the same result. In addition, it would be interesting in a later study to assess fatigue resistance instead of the MVC and thus eliminate the limitations of the study through the MVC measurement.

Furthermore, by using video analysis, which measures throughout the pelvis to the foot, additional qualitative running parameters could be analysed. A two-dimensional (2D) video-based assessment of running kinematics using a high-speed camera is a common clinical approach given the space, time and cost burdens present with a computerized 3-dimensional analysis. Several body posture and alignment measures such as reaction forces, joint moment and forces and tissue loads that are associated with musculoskeletal injury can be observed and analyzed [1 77].

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