Sex Differences in Running Performance: The Role of the Anaerobic Speed Reserve in Female Middle-Distance Running

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SEX DIFFERENCES IN RUNNING PERFORMANCE: THE ROLE OF THE ANAEROBIC SPEED RESERVE IN FEMALE MIDDLE-DISTANCE RUNNING

By

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Bachelor of Science: Biological Sciences, The University of Birmingham 2018

THESIS
Submitted in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

Middle-distance running is an interesting domain in which to study sex differences in athletic performance because of the varied metabolic, mechanical and tactical demands. The Anaerobic Speed Reserve (ASR) represents the difference between an athlete’s maximal sprint speed (MSS) and maximal aerobic speed (MAS). The ASR and MSS are key determinants of elite male 800m performance (Sandford et al., 2018); however, the role of the ASR in female middle-distance running is unclear, considering sex differences in physiology, mechanics and competition factors. We found that sub-groups of female middle-distance runners could be distinguished using the ASR and speed reserve ratio (SRR = MSS/MAS),
illustrating diversity in metabolic and mechanical profiles. The ASR and MSS had no significant relationship with 800m time; instead, measures of aerobic power appear to underpin 800m performance in this sub-elite female cohort. This information may assist coaches and practitioners to individualize training protocols for female middle-distance runners.
# TABLE OF CONTENTS

## LIST OF FIGURES

viii

## LIST OF TABLES

ix

## SYMBOLS/ ABBREVIATIONS

x

## CHAPTER 1: INTRODUCTION

1

### Purpose of the Study

4

### Hypotheses

5

### Scope of the Study

5

### Limitations

6

### Assumptions

7

### Significance of the Study

8

### Definition of Terms

8

## CHAPTER 2: REVIEW MANUSCRIPT

12

### Abstract

13

### Introduction

15

### Explanations

30

### Practical Applications

39

### Conclusions

41

### References

43

## CHAPTER 3: RESEARCH MANUSCRIPT

53

### Abstract

55

### Introduction

57
Methods.................................................................................................................. 60
Results....................................................................................................................... 65
Discussion............................................................................................................... 68
Practical Applications............................................................................................. 74
Conclusions............................................................................................................ 74
References............................................................................................................... 76

CHAPTER 4: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS....... 81
Summary................................................................................................................... 81
Conclusions.............................................................................................................. 82
Recommendations.................................................................................................... 83

APPENDICES.......................................................................................................... 86
Appendix A. Informed Consent................................................................................... 87
Appendix B. Health History Questionnaire.................................................................. 93
Appendix C. Data Collection Sheet............................................................................ 95

REFERENCES......................................................................................................... 99
LIST OF FIGURES

Chapter 2: Review Manuscript Figures

Figure 1. The Sex Gap Over Time in Running Events 100m to Marathon between 2001–2020 .......................................................................................................................................................... 23

Figure 2. The Sex Gap and Performance Level in Running Events 100m to Marathon ........................................................................................................................................................................... 29

Chapter 3: Research Manuscript Figures

Figure 1. Relationship between Season's Best 800m Performance Time and ASR Components .......................................................................................................................................................... 68
LIST OF TABLES

Chapter 2: Review Manuscript Tables
Table 1. The World Record (WR) times and year for Males and Females, and the WR Sex Gap for Running Events 100m to Marathon........................................... 17

Chapter 3: Research Manuscript Tables
Table 1. Descriptive Characteristics of Female Middle-Distance Runners Classified into Sub-Groups................................................................. 66
Table 2. Performance Variables of Female Middle-Distance Runners Classified into Sub-Groups........................................................................ 67
SYMBOLS/ABBREVIATIONS

>: greater than

<: less than

#: number

%: percent

%BF: percent body fat

°C: degrees Celsius

±: plus or minus

~: approximately

ASR: anaerobic speed reserve

ATP: adenosine triphosphate

bpm: beats per minute

ES: effect size

kg: kilograms

km: kilometer

km/hr: kilometres per hour

LT: lactate threshold

m: meters

m/s: meters per second

MAS: maximal aerobic speed

min: minutes

ml: milliliters

mmol: millimole
mph: miles per hour
ms: milliseconds
MSS: maximal sprint speed
n: number of participants
OG: Olympic games
s or sec: seconds
SB: season’s best time
SD: standard deviation
SRR: speed reserve ratio
v4mmol: velocity at onset of blood lactate accumulation
VO2max: maximal oxygen consumption
VO2peak: peak oxygen consumption
vVO2max: velocity at VO2max
WC: world championships
WL: world lead
WR: world record
CHAPTER 1

Introduction

The role of the sports scientist and coach alike is to understand the strengths and weaknesses of their athlete, as well as the demands of their sporting event, and integrate this information to design practices to optimize performance. Through scientific research and experience, more is being understood about the diversity of athlete profiles and the complex requirements of successful sports performance (Brandon, 1995; Sandford & Stellingwerff, 2019).

Middle-distance running, which encompasses events lasting ~1.5 to 5 min in duration (800m, 1,500m, Mile) (Sandford & Stellingwerff, 2019), is an interesting domain in which to explore such topics. The literature on middle-distance running includes focuses on energetics (Duffield & Dawson, 2003; Nummela et al., 1996; Thompson, 2017), biomechanics (Cunningham et al., 2013; Thompson, 2016; Thompson, 2017), tactics/pacing (Filipas et al., 2018; Hanley & Hettinga, 2018; Hanley et al., 2018; Hettinga et al., 2019; Sandford et al., 2017; Sandford et al., 2019a), training responses (Billat, 2001; Ingham et al., 2012) and the prediction of race performance (Ali Almarwaey et al., 2003; Bachero-Mena et al., 2017; Bellinger et al., 2020; Ingham et al., 2008; Yoshida et al., 1990). From a physiological and mechanical perspective, middle-distance running (particularly the 800m event) represents the intermediate between endurance and speed-based territories (Brandon, 1995; Thompson, 2017). As such, understanding how to achieve optimal performance in middle-distance running offers a unique challenge to coaches, practitioners and researchers. Whilst the aerobic determinants of middle-distance
running have been well described and are the foundation of coaching education (Berg, 2003), less is known and understood about the anaerobic component (Brandon, 1995; Nummela et al., 1996) or biomechanical and neuromuscular factors (Bachero-Mena et al., 2017; Sandford et al., 2019b; Thompson, 2016; Thompson, 2017). Unlike the aerobic domain, there are no direct means of measuring anaerobic energy expenditure, making it difficult to confidently assess the relationship between anaerobic energetics and middle-distance performance (Brandon, 1995; Bundle et al., 2003; Bundle & Weyand, 2012; Haugen et al., 2018).

Furthermore, there is a sex bias in the middle-distance running literature towards studying male participants, with few studies focusing specifically on female performance (Mpholwane, 2007). This is of significance because there are sex differences in hormonal profiles (Handelsman et al., 2017), anthropometrics and muscle anatomy (Costill et al., 1976; Sandbakk et al., 2017), metabolism (Duffield & Dawson, 2003; Duffield et al., 2005), biomechanics (Nuell et al., 2019; Slawinski et al., 2015; Williams & Welch, 2015) and injury profiles (Hollander et al., 2021) of runners, which could mean the event demands and responses to training are different in females than males. Moreover, there are differences in pacing behaviors and the tactical challenges of male and female middle-distance competition (Filipas et al., 2018; Hettinga et al., 2019) which should inform sex-specific training practices and race preparation. Research has been conducted on the evolution of the sex gap in athletics, i.e., the percentage difference between absolute male and female performance time. It appears that the drastic narrowing of the sex gap which took place during the 20th century has now stabilized around 10 – 12% for middle-
distances and other running disciplines (Cheuvront et al., 2005; Millard-Stafford et al., 2018; Thibault et al., 2010). However, an updated analysis on performance data from a small group of the top ranked male and female runners is warranted to better understand differences in absolute performance and competition depth between the sexes. As such, more research should explore the sex differences in middle-distance running performance, and coaches and practitioners should apply this knowledge to ensure female athletes implement the most effective training practices for their sex.

There is a small yet growing body of literature that applies the Anaerobic Speed Reserve (ASR) concept to male middle-distance running (Bellinger et al., 2020; Sandford et al., 2018; Sandford et al., 2019b; Sandford et al., 2019c; Sandford & Stellingwerff, 2019). The ASR is defined as the difference between an athlete’s maximal sprint speed (MSS) and maximal aerobic speed (MAS) (Billat et al., 1994). The ASR construct provides a framework for understanding the diversity of physiological and mechanical profiles of middle-distance runners and can be used to separate male 800m runners into ‘sub-groups’: 400–800m runners, 800m specialists and 800–1500m runners (Sandford et al., 2018; Sandford & Stellingwerff, 2019). The speed reserve ratio (SRR), calculated as MSS divided by MAS, is an ASR construct that can be used by coaches and practitioners to summarize the MSS and MAS characteristics of an athlete within a single value. Sandford et al. (2018) identified a pattern of decrease in SRR values from 400–800m runners to 800m specialists to 800–1500m runners, reflecting their underlying physiological and mechanical differences. Additionally, the ASR can be used in studies of race prediction to better
understand the key determinants of successful performance. For example, in elite male 800m runners, a large ASR and fast MSS are key predictors of race performance, illustrating the importance of sprint ability and high-speed demands in this event (Sandford et al., 2018). There is very limited data on the ASR in female middle-distance runners (Bellinger et al., 2020; Sandford & Stellingwerff, 2019). Considering the sex differences in many factors that underpin athletic performance, the role of the ASR and MSS in female middle-distance running is unclear. Whilst anaerobic power outputs have been correlated with female 800m time (Mpholwane, 2007; Yoshida et al., 1990), most of the literature focuses on aerobic variables being very strong predictors of performance (Ali Almarwaey et al., 2003; Ingham et al., 2008; Yoshida et al., 1990). Moreover, the estimated anaerobic energy contributions to 800m and 1,500m running are lower in females than males (Duffield & Dawson, 2003; Duffield et al., 2005), which may have implications for the significance of the ASR in female middle-distance running. More attention should be given to this topic area in order to better understand the demands of female middle-distance running and to equip female athletes to excel in their sport.

**Purpose of the Study**

The objectives of this thesis study were: 1) to use the ASR construct to characterize the physiological and mechanical profiles of a cohort of female middle-distance runners; 2) to evaluate the relationship of ASR and related variables including SRR, MSS, and MAS to 800m performance time in female middle-distance runners; 3) to
compare the role of the ASR between males and females, based on the current literature on male middle-distance runners and the present data on females.

**Hypotheses**

The following hypotheses were tested in this study:

**Hypothesis 1:** Female middle-distance running sub-groups can be separated on the basis of their ASR characteristics. 400m–800m runners have a larger ASR and SRR, faster MSS and slower MAS than 800m–Mile runners.

*Rationale:* Middle-distance runners display diverse physiological profiles (Brandon, 1995) and male 800m sub-groups can be distinguished using the ASR, SRR, MSS and MAS (Sandford et al., 2018).

**Hypothesis 2:** There is a relationship between the ASR and associated constructs (SRR, MSS, MAS) with 800m performance time in female runners (non-directional).

*Rationale:* There is a negative relationship between the ASR and 800m performance time in male 800m runners (Sandford et al. 2018). However, aerobic energy contribution during 800m running is higher in females than males (Duffield et al. 2005).

**Scope of the Study**

Female runners (N=12) between the ages of 18 and 25 years who were competing in middle-distance track races were assessed for MAS and MSS to determine their ASR and SRR. Participants were assigned to either 400m–800m or 800m–Mile sub-groups in order to assess sub-group differences in the ASR and associated
constructs. The relationships between these variables and season’s best 800m performance time were assessed.

**Limitations**

The following limitations were identified in this study:

1. The sample in the present study were well-trained female runners who had previously or were currently competing in collegiate track races. This limits generalizability of the findings to female runners of a similar caliber, and conclusions cannot be drawn regarding the role of the ASR in elite female 800m running.

2. The sample consisted of a relatively heterogenous group of runners in relation to their season's best 800m time. This could change what variables are the most important predictors of performance in comparison to the homogenous population used in Sandford et al.'s (2018) study.

3. We separated participants into one of two sub-groups (400m–800m or 800m–Mile), instead of the three sub-groups identified by Sandford et al. (2018) (400m–800m athletes, 800m specialists, 800m–1500m athletes). This was due to sample size limitations.

4. We used a different method of statistical analysis than Sandford et al. (2018) - null hypothesis testing vs. Magnitude Based Inferences - which may have impacted the validity of the comparisons made between the study findings and the subsequent conclusions drawn.
5. We used a novel protocol to assess MAS (vVO$_2$max) and there is no agreement within the literature on how to define or measure MAS. We cannot be certain that our protocol provided the most valid measure of the participants’ MAS.

6. We assessed MSS using an electronic timing system (Freelap Pro BT424, Freelap USA, Pleasanton CA) that is yet to be validated within the literature. We were required to measure MSS on an outdoor all-weather Athletics Track, and, therefore, could not rule out the possibility that environmental variables, including wind speed and temperature, impacted the MSS assessment for some or all participants.

7. Race performance data was collected within 12 weeks of the initial assessment. We cannot rule out the possibility that a participant’s MAS and/or MSS changed from the time of assessment to when they ran their season’s best 800m.

8. We were unable to meet the target sample size and unable to collect data from all participants enrolled in the study due to cancellation of track races at the start of the COVID-19 pandemic.

Assumptions

The following assumptions were identified in this study:

1. The season’s best 800m time was a valid achievement marker that reflected participants’ maximal performance at the time of testing.
2. Participants gave maximal effort during the MAS and MSS assessments and followed the pre-test guidelines (Appendix A).

3. The MAS protocol that was developed in this study enabled a valid assessment of \( \text{vVO}_2\text{max} \).

4. Environmental conditions (wind speed and temperature) had no impact on the MSS assessment.

5. Participants were assigned to appropriate sub-groups based on the training and competition criteria used.

**Significance of the Study**

This study was, to the author's best knowledge, the first to investigate the role of the ASR in female 800m running. Whilst it is recognized that the ASR is an important component of male 800m running (Sandford et al. 2018; Sandford et al. 2019b), it is yet to be established whether the same is true for females. This is an important question to address in order to understand how female middle-distance runners can better prepare to meet the demands of their event and what is required to achieve medal winning race performances. Additionally, this study has the potential to recommend how female runners can be profiled and assigned to middle-distance sub-groups using the ASR and associated constructs, with implications for individualized training interventions and racing strategies.

**Definition of Terms**

400m–800m sub-group: Speed-based 800m runners.
**800m–Mile sub-group:** Endurance-based 800m runners.

**Aerobic energetics:** Oxygen dependent ATP production.

**Anaerobic energetics:** Non-oxygen dependent ATP production.

**Anaerobic Speed Reserve:** The difference between maximal sprint speed and maximal aerobic speed.

**Biomechanics:** The study of human movement applying the science of mechanics.

**Doping:** the illegal use of performance-enhancing drugs in sport.

**Elite level:** The best athletes competing in their sex-specific event, at a professional level and/or at major international championships.

**Enduring competitiveness hypothesis:** there are innate and evolved sex differences in psychology and males have a predisposition to engage in competitive tasks.

**Flat Olympic distances:** Running disciplines in the Olympic athletics program including 100m, 200m, 400m, 800m, 1,500m, 5,000m, 10,000m, Marathon (42.195km).

**Gender:** The attitudes, feelings, and behaviors that a given culture associates with a person's biological sex.

**Grassroots level:** Sports and activities performed at a local level, often part of community-driven movements.

**Long-distance events:** Running disciplines longer than ~5 min (typically 3,000m, 5,000m, 10,000m, Marathon).

**Maximal Aerobic Speed or \( v\text{VO}_2\text{max} \):** The minimal running speed required to elicit maximal oxygen consumption.
Maximal Sprint Speed: Top end running speed.

Middle-distance events: Running disciplines lasting ~1.5 to 5 min in duration (typically 800m, 1,500m, Mile).

Neuromuscular: Function and integration of the nervous and muscular systems to control and direct movement of the body.

Recreational level: Individuals who engage in sport or physical activity, but do not train or compete at a level comparative to the sub-elite or elite.

Running endurance: Ability to sustain running speeds for an extended period of time.

Sex: A person’s biological status, typically characterized as male, female or intersex.

Sex gap: The difference between absolute male and female performance, expressed relative to male performance.

Sociocultural conditions hypothesis: there exists sex differences in opportunities and participation in sport that explain part of the variance between male and female performance.

Speed application: The skills and abilities to achieve high running velocities.

Speed Reserve Ratio: Maximal sprint speed divided by maximal aerobic speed.

Sprint ability: A technical ability limited by neuromuscular or mechanical variables, includes running performance <60s.

Sprint events: Running disciplines lasting <60 seconds (typically 100m, 200m, 400m).

Sub-elite level: Athletes who are well trained but compete below the elite level (can include high-school and college athletes).
Title IX: Title IX of the Education Amendments of 1972, a federal law in the United States that prohibited discrimination based on sex in education.

Ultra-distance events: Running disciplines lasting 6 hours or longer in duration.

VO2max: Maximal rate of oxygen consumption.

World Athletics: International governing body for the sport of athletics.

World lead: The annual fastest/highest/farthest sex-specific mark achieved in an athletics event.

World record: The all-time fastest/highest/farthest sex-specific mark achieved in an athletics event.
CHAPTER 2

Review Manuscript

This chapter presents a review manuscript written for submission to *Sports Medicine* journal, titled “Expanding the Gap: An Updated Look into Sex Differences in Running Performance”. The references cited in this review are provided at the end of the chapter and follow the standards set by the journal. Tables and figures are embedded in the text. This review manuscript is authored by Lydia Hallam and Fabiano Amorim.
Title: Expanding the Gap: An Updated Look into Sex Differences in Running Performance

Preferred Running Head: The Sex Gap in Running Performance.

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Abstract

Males consistently outperform females in athletic endeavors, including running events of standard Olympic distances (100m to Marathon). The magnitude of this percentage sex difference, i.e., the sex gap, has evolved over time. Two clear trends in sex gap evolution are evident; a narrowing of the gap during the 20th century, followed by a period of stability thereafter. However, an updated perspective on the average sex gap from top 20 athlete performances over the past two decades reveals nuanced trends over time, indicating the sex gap is not fixed. Additionally, the sex gap varies with performance level; the difference in absolute running performance between males and females is lowest for world record/world lead performances and increases in lower ranked elite athletes. This observation of an increased sex gap with world rank is evident in events 400m and longer and indicates a lower depth in female competitive standards. Explanations for the sex difference in absolute performance and competition depth include physical (physiological, anatomical, neuromuscular, biomechanical), sociocultural, psychological and sport-specific factors. It is apparent that females are the disadvantaged sex in sport; therefore, measures should be taken to reduce this discrepancy and enable both sexes to reach their biological performance potential. There is scope to narrow the sex performance gap by addressing inequalities.
between the sexes in opportunities, provisions, incentives, attitudes/perceptions, research and media representation.

Declarations

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Expanding the Gap: An Updated Look into Sex Differences in Running Performance

1. Introduction

Performance differences between males and females, herein called the “sex gap”, have been studied across sporting events, including athletics, swimming, cycling and rowing [1–9]. The best male athletes consistently outperform their female peers, with the magnitude of this sex gap typically ranging between 5 – 17%, depending on the sporting discipline, event duration and competitive standard. For example, the average sex gap for elite level running is 10.7%, compared to 17.5% for jumps, 8.9% for swimming, and 8.7% for sprint cycling [9]. In athletics the sex gap is usually lower for sprints than middle- and long-distances [1,3,5]. The sex gap within ultra-endurance events is as low as 4.4% in ultra-marathon [10]. Finally, the sex gap is smaller between elite males and females [1,9], compared to sub-elite and recreational runners [11,12].

The sex gap in sports performance is primarily rooted in biological differences between the sexes, namely in relation to male’s superior skeletal muscle mass, oxidative capacities and lower fat mass [2]. However, there is a range of sociocultural, psychological and sport-specific factors that could explain some of the variance between male and female athletic performance [13–17]. The relative contribution of these different biological and environmental factors to the sex gap is unclear. Therefore, the aims of this review manuscript are three-fold: a) provide a summary of the literature on the evolution of the sex gap in running performance, b)
provide an updated analysis on the running sex gap to explore if and how the sex gap has changed in recent years across running events and between performance levels, c) summarize potential explanations. We chose to focus on the sport of running, specifically flat Olympic distances, because of the availability of result databases and literature on the sex differences in running physiology and performance. Addressing these questions provides insight into the debate surrounding the limits of human athletic performance [18] and hold practical significance for athletes, coaches and practitioners.

1.1. The Evolution of the Sex Gap: World Records and World Lead Performances

Analyses of world record (WR) performances between 1891 – 2008 reveal two major trends in the sex gap evolution for athletic events: a fast reduction in gap magnitude until the mid-1980s, followed by a period of stability thereafter [9]. Within running disciplines 100m to Marathon distance, the sex gap in WRs decreased from an average of 30% in 1922 to 10.7% at the point of stabilization (~1985) [9]. Table 1 shows the WR sex gaps for specific running events at the established stabilization year (based on Thibault et al.’s analysis [9]), as of 2004 [1] and the present day (February 2021). From the mid-1980s to present, there has been an increase in the WR sex gap for all flat Olympic running events, except the 5,000m and Marathon, where the gap has narrowed slightly (Table 1).
Table 1. The World Record (WR) times and year for Males and Females, and the WR Sex Gap for Running Events 100m to Marathon [1,9]

<table>
<thead>
<tr>
<th>Running Distance</th>
<th>Male WR Time (Year set)(^a)</th>
<th>Female WR Time (Year set)(^a)</th>
<th>WR sex gap (%) during 20(^{th}) century, taken from Thibault et al. [9](^b)</th>
<th>WR sex gap (%) as of 2004, taken from Cheuvront et al.[1](^b)</th>
<th>WR sex gap (%) as of February 2021(^{b,c})</th>
</tr>
</thead>
<tbody>
<tr>
<td>400m</td>
<td>43.03 (2016)</td>
<td>47.60 (1985)</td>
<td>10.0</td>
<td>10.2</td>
<td>10.6</td>
</tr>
<tr>
<td>800m</td>
<td>1:40.91 (2012)</td>
<td>1:53.28 (1983)</td>
<td>10.4</td>
<td>12.0(^c)</td>
<td>12.3</td>
</tr>
<tr>
<td>5,000m</td>
<td>12:35.36 (2020)</td>
<td>14:06.62 (2020)</td>
<td>12.9</td>
<td>14.1</td>
<td>12.1</td>
</tr>
<tr>
<td>10,000m</td>
<td>26:11.00 (2020)</td>
<td>29:17.45 (2016)</td>
<td>10.8</td>
<td>12.1</td>
<td>11.9</td>
</tr>
</tbody>
</table>

\(^a\) Time format ss.ms, mm:ss.ms, h:mm:ss

\(^b\) The sex gap (%) is calculated as follows: \([(\text{Female WR (s)} – \text{Male WR(s)})/ \text{Male WR(s)}] \times 100\)

\(^c\) Calculated using data from World Athletics public database (https://www.worldathletics.org)

The trends in the sex gap for WR running performances - rapid decline followed by a period of stability - reflect the changes in the rate at which females were setting WRs compared to males. An analysis of WR progressions reveal that there were significant initial jumps in the rate of female WR advancement which eventually plateaued; whereas, the advancement of male WRs was more gradual throughout the 20\(^{th}\) century and into the 21\(^{st}\) century [1]. This reflected the advancement in
training, globalization of sport, increase in competitive opportunities and professionalism throughout the 20th century [2,19]. Females began competing in sport later than males and were exposed to these changes within a shorter time frame, prompting a drastic fall in female running times unrivalled by that of males [2]. This trend led some to predict that females would eventually outrun males [20]; however, it is apparent that the rate of improvement in female WR performances have levelled, and the sexes now ‘evolve in parallel’ [9]. However, the present-day WR sex gaps are slightly wider than they have been in the past (Table 1), and males appear to be breaking WRs more frequently than females [21]. As such, males may be improving at a greater rate than females at the world class level.

Considering many female WRs have not been surpassed since the 1980s (Table 1), it is also insightful to consider progression in the annual world lead (WL) performances for both sexes. Sparling et al. found the sex gaps for WL 1,500m and Marathon performances were relatively stable between 1980 – 1996, averaging at 11.1% and 11.2%, respectively [22]. This indicates that the magnitude and trends in the WL sex gap are similar to that of WR performances [1].

The literature on the sex gap evolution in running often focuses on changes in WR or WL performances [1,9,22,23]. Whilst these analyses give insight to the upper limits of human performance [5], we should be cautious when drawing conclusions about general trends in the sex gap based on these rare and extraordinary individual performances [13]. These studies use a single data point per year (i.e., percent
difference between the #1 ranked male and female); therefore, ‘anomalous’ performances could skew the trends and subsequent conclusions drawn. This is of concern within the context of doping scandals and whether some WRs were achieved by athletes taking performance-enhancing drugs. World Athletics have considered a proposal to erase all WRs set before 2005, the year when blood and urine samples were first stored for future testing [24]. If this reset took place, the sex gap for some events would be impacted quite drastically, for example the women’s 100m WR gap would increase from 9.5% to 11.1%. This brings into the question the relevance of studying WRs to understand the sex gap evolution, since such records may not always be reliable or trustworthy markers of the natural limits of human performance.

1.2. The Evolution of the Sex Gap: Elite Performances

Whilst coaches, athletes, scientists and sports teams are looking to push the limits of human athletic performance by achieving WR times, the world of high-performance sport is also concerned with advancing competitive standards within the elite category as a whole. Looking beyond WRs/WLs and taking the average sex gap between a small group of the top ranked male and female runners will expand the pool of data analyzed each year. This can provide a more representative picture of trends in the sex gap evolution for world class runners and allow detection of changes not reflected in WRs/WLs alone [7,13,23]. Such an approach would also
help account for the confounding effect of performances achieved by doping and/or anomalies in sport.

A few studies have adopted this approach [3,7,9]. Millard-Stafford et al. compared the top 8 male and female performers at the U.S. Olympic track and field Trials and found the average sex gap for running events was 12.1% in 2016, which had been stable since 1980 [3]. The gap had decreased from 17.3% in 1972 following the instigation of Title IX, a federal law which legislated equal opportunities for females in the USA education system, including within sport. Additionally, Thibault et al. examined the sex gap evolution using the top 10 male and female running performances in athletics worldwide [9]. The average gap decreased from 25.3% in the early 20th century to 11.2% in 1984, after which followed a stabilization period [9]. Seiler et al. studied the sex gap between the top 6 finishers in male and female World Championship and Olympic Games finals for sprint events. The average sex gap for the 100m, 200m and 400m events decreased between the 1950s – 1980s to reach an average low of 9.8%, before increasing to 11.2% by 2005 [7].

Moreover, the patterns in the sex gap evolution are similar when studying the elite pool and WR/WL performances - rapid decline until the 1980s then stabilizing [9]. However, as demonstrated by Seiler et al., looking at the top 6 annual performances at major championships allows sensitivity to detect the widening of the sex gap over a shorter time frame in more recent years [7]. It is unclear whether a similar change has occurred in middle- and long-distance running events, or if there are trends that
have occurred in the sex gap in the last decade. Further, the above studies are insightful but limited because they only consider performances from a single nation/at a single event (U.S. Olympic Trials [3]), or do not include the most recent years’ data on sex gaps (data until 2008 [9], data until 2005 [7]).

1.3. An Update on the Sex Gap in Running Performance

1.3.1. Sex Gap Trends for Top 20 Performances over the last 20 Years

Understanding trends in the sex gap in the modern athletic era will give insight into the current competitive standard of male and female running and how the sexes perform relative to one another. This should guide discussion around explanations for the sex gap and how to advance athletic performance in both sexes.

We conducted an up-to-date analysis on the sex gap between elite male and female runners using the annual top 20 world best performances over the past two decades. Data was extracted from the World Athletics public database (https://www.worldathletics.org, Season Top Lists, date extracted: 02/01/2021), with the top 20 best by athlete marks selected for male and female Olympic running distances (flat events: 100m, 200m, 400m, 800m, 1,500m, 5,000m, 10,000m, Marathon) each year between 2001 – 2020. For each event and each year, a pairwise comparison was made between the nth ranked male and female performance time (seconds), using the following equation:
Sex gap (%) = [(Female\textsubscript{n} (s) – Male\textsubscript{n} (s))/ Male\textsubscript{n} (s)] X 100

For each event each year, the average sex gap across all 20 ranks was calculated as follows:

\[ \text{Top 20 sex gap} (%) = \frac{\sum \left[ \frac{(\text{Female}_n (s) - \text{Male}_n (s))}{\text{Male}_n (s)} \right] \times 100}{20} \]

As per Seiler et al. [7], we did not analyse the data with inferential statistics, considering data points were compiled from multiple individuals across multiple years. The sex gap (%) in performance time for each pairwise rank was plotted against historical time (year) using GraphPad Prism 8 (San Diego, CA) for each running event. Two regression lines were fitted to the data: a linear regression \( y = ax + b \) and a second order polynomial regression \( y = ax^2 + bx + c \). If the R\(^2\) value was improved by at least 0.02 when using the second order polynomial regression, this was used as the line of best fit, otherwise the linear regression was used [7].

As inferred from the regression lines plotted to the data (Fig. 1a – 1h), the sex gap for top 20 performers over the past two decades has been relatively stable for the 100m, 200m and 800m events, has increased slightly for the 400m, has decreased slightly for the 1,500m and 5,000m, and has fluctuated for the 10,000m and Marathon. The current trends in the top 20 sex gap for sprints (100m, 200m, 400m), middle-distances (800m, 1,500m) and long-distances (5,000m, 10,000m, Marathon) will be discussed in relation to the WR sex gaps and the literature below.
Fig. 1 The Sex Gap Over Time in Running Events 100m to Marathon between 2001–2020. The sex gap % is calculated as the percent difference between male and female running times. The pairwise sex gaps for each top 20 ranked individuals (annually, worldwide) are plotted as black circles and the average top 20 sex gap for each year is plotted as a red diamond. Regression lines are fitted as the line of best fit.
In accordance with other studies [3,5], the present analysis shows that the top 20 sex gap for sprinters (specifically 100m and 200m) is consistently lower than middle- and long-distance runners over the years (Fig. 1). The average top 20 sex gap for the 100m ranges from 9.75% to 11% between 2001 – 2020 (Fig. 1a), consistently higher than the current 100m WR sex gap of 9.5% (Table 1). For the 200m, the average top 20 gap is, on occasion, similar to the WR sex gap of 11.2%, but most years it exceeds 11.5%. The 400m top 20 sex gap has exceeded 12% every year in the past two decades, whereas the WR sex gap is 10.6%.

Seiler et al. observed a narrower sex gap in the sprints in the 1980s compared to the 2000 – 2005 period [7]. This may have been an artefact of doping prior to the initiation of randomized drug testing in 1989; the gains that male athletes receive from performance-enhancing drugs may be smaller than that of females due to the male’s pre-existing high levels of circulating testosterone [7]. It appears that since the early 2000s, the average sex gap has not changed drastically for the 100m or 200m and may be increasing very slightly in the 400m (Fig. 2). This implies that the confounding effect of performance-enhancing drugs are minimized, allowing a more accurate assessment of the limits of male and female performance.
The average top 20 sex gaps for the 800m and 1,500m exceeded 13% in all but one year, and the present WR sex gaps for these events are 12.3% and 11.7%, respectively (Table 1). Similarly, Thibault et al. established the stable sex gap for the top 10 800m and 1,500m performances at 11.3% and 12.3%, compared to 10.4% and 10.6% for WR performances, respectively [9].

The sex gap in elite 1,500m appears to have decreased in recent years (Fig. 1e), an insight which is not apparent based on earlier studies [9,22]. Whilst speculative, the narrowing of the gap could reflect rising standards of elite female 1,500m, particularly amongst British and American runners. Between 2005 – 2008, either no athletes or a single female athlete was represented by these countries on the top 20 world rankings. In comparison, four American and four British female runners were ranked in the top 20 in 2019. Whilst the WR sex gap has not narrowed significantly since 2004 (Table 1), the top 20 sex gap for 1,500m is ~1% lower, and it will be of interest to see if this trend continues.

The overall trend in the 800m sex gap is stable based on the fitted regression line (Fig. 1d), which is consistent with the findings of Thibault et al. [9]. However, visual inspection of the graph reveals nuances in 800m sex gap evolution; there is a cyclical trend in the sex gap - decreasing between 2001 – 2008, then increasing to 2013, decreasing to 2017 before increasing in the subsequent 3 years.
Long-distance

On average, the top 20 sex gap was highest of all running events for the 10,000m. There was no systematic increase in the sex gap with increasing event distance as suggested elsewhere [5], since the 5,000m and Marathon gaps were typically lower than that of the middle-distances (Fig. 1).

The sex gap has narrowed in recent years for the 5,000m (Fig. 1f); at the start of the era (early 2000s), the sex gap appeared relatively stable around 13.8%, yet has been ~1 – 2% lower in comparison in the last 5 years (with the exception of 2018). Alongside this, there appears to be a concomitant narrowing of the sex gap in the 5,000m WR; in 2004 this was 14.1%, compared to the current gap of 12.1% (Table 1).

As seen in Fig. 1g, there is large annual variability and fluctuations in the sex gap for the 10,000m. This is not particularly evident in the sprints and middle-distances, where year-on-year variations in the sex gap are smaller and more cyclical. The average top 20 sex gap for the 10,000m was lowest at 12.8% in 2016 and highest at 16.2% in 2007, and consistently higher than the current WR sex gap of 11.9% (Table 1).

The Marathon event also displays similar variability in the sex gap, with an overall inverted-U shape trend, increasing for the first decade then decreasing (Fig. 1h).
The average sex gap always exceeded 12%, compared to the current Marathon WR sex gap of 10.2%. Moreover, Hunter et al. found that, between the late 1990’s – 2009, the average sex gap for the top 5 runners at major world class marathon races differed significantly over the years; although, there was no systematic trend to indicate the sex gap narrowing or widening [4].

These observations indicate that, although there may be overall stability in the sex gap for the longer distances, annual changes occur in how females perform relative to their male peers, and vice versa. Whilst it is currently unclear why such variations exist it could be inferred that multiple underlying variables are involved.

1.3.2. Changes with Performance Level over Top 20 Ranks

To further understand the relationship between the sex gap and performance level, we averaged the sex gap across the 20-year period (2001 – 2020) for each rank position (1st to 20th) using the pairwise sex gaps for the top 20 performers across Olympic running events. For each event (100m to Marathon), we plotted the averaged sex gap against rank position.

As illustrated in Fig. 2, the overall trend for most running events is an increase in the sex gap as the rank increases from the 1st to 20th athlete. For the sprint events (Fig. 2a), the increase in sex gap with rank is most clearly seen for the 400m. For the 100m, the sex gap actually decreases from 1st to 4th ranked individuals, increases to
the 15\textsuperscript{th} rank, then plateaus. For the 200m, the gap is highest for the first three ranked individuals and is relatively similar between 4\textsuperscript{th} and 20\textsuperscript{th} ranks. For the middle-distances (Fig. 2b), changes in sex gap with rank position are similar; there is a clear trend towards a gradual expanding of the sex gap from 1\textsuperscript{st} to 13\textsuperscript{th} rank, after which the gap is relatively stable at \~14\% for higher ranks. There is a linear trend of increase in the 5,000m sex gap from 1\textsuperscript{st} to 20\textsuperscript{th} ranked athlete. For the 10,000m and Marathon, there is a relatively large jump in the sex gap from 1\textsuperscript{st} to 4\textsuperscript{th} rank, and a more gradual expansion of the gap with each rank position thereafter. The difference in average sex gap between 1\textsuperscript{st} and 20\textsuperscript{th} ranks is smallest for distances 100m to 1,500m (<1\%), and larger for 5,000m to Marathon (1.3 – 2.1\%).

The widening of the sex gap with rank position or finishing place in elite level runners is evident in other studies [4,22,25–27]. The sex gap increases from the WL performers to the 100\textsuperscript{th} ranked athletes in the 1,500m [22] and Marathon [22,26], from the 1\textsuperscript{st} place to 5\textsuperscript{th} place finisher [4] and 1\textsuperscript{st} to 10\textsuperscript{th} place finisher [25,27] in world class marathon races. This is due to a greater relative drop off in performance time with increasing rank/position for female athletes [25].

Collectively, these findings indicate that male athletes are relatively faster runners and closer to the sex specific WR/WL marks than females, and that the competitive pool of male runners is more homogenous. This is more apparent in middle- and long-distance running than in short sprints, where the sex gap is not noticeably different between 1\textsuperscript{st} and 20\textsuperscript{th} world class ranks (Fig. 2). Nonetheless, there is
evidence of a greater drop off in female performance at lower performance levels for sprinters; the sex gap for sub-elite sprinters is 15% across 80m [12], which is higher than the 100m sex gap for WR and elite performances. Moreover, there is a sex gap in relative performance and depth of competition within running.

Fig. 2 The Sex Gap and Performance Level in Running Events 100m to Marathon. The sex gap % is calculated as the percent difference between male and female running times, averaged over a 20-year period (2001 – 2020) for each worldwide rank position (1 through 20) for a) sprint events, b) middle-distances, c) long-distances.
2. Explanations

Underpinning differences in running performance between males and females are a range of potential physical (physiological, anatomical, neuromuscular, biomechanical), sociocultural, psychological and sport-specific factors. The role each variable contributes to the sex gap may vary between event disciplines, across historical time, across cultures, and with performance level. Many assert that the gap in running today is explained purely by biological sex differences [1,3,9]. However, there are fluctuations and small changes in the sex gap for WRs (Table 1) and elite level running (Fig. 1), which warrant further investigation into other explanatory factors. This has significance to the discussion of whether runners, both male and female, have reached the limits of human performance, or whether advancements in technology, training, opportunities and talent identification could see notable jumps in one or both of the sexes [18]. The following section will discuss the biological and environmental explanations for the sex gap in running performance.

2.1. Physiological, Anatomical, Neuromuscular & Biomechanical Explanations

2.1.1. Sprints

The sex differences in muscle anatomy and physiology are significant in explaining the performance gap in sprint running. Male runners have superior muscle volumes than females [12], due to longer muscle segment sizes and ~25 – 40% more skeletal
muscle mass [23]. The latter is due to male’s larger muscle fiber cross sectional areas, as opposed to greater fiber numbers [28,29]. Since muscle cross sectional area is closely related to the force producing capacity of the muscle [29], males are naturally stronger and more powerful than females, contributing to their advantage in sprinting [23]. Additionally, males have superior anaerobic metabolic power than females [23], potentially due to a larger relative area of fast twitch muscle fibers which have large glycolytic capacity [28] and higher peak tension [30]. These differences in muscle morphology and function arise during puberty and are underpinned by the increase in circulating testosterone in males [31].

Biomechanical and neuromuscular factors are also pertinent to this discussion for sprinters. It is apparent that sprint speed is limited by the ability to apply large ground reaction forces over short contact times, as opposed to the anaerobic energy supply [32]. Male sprinters possess anthropometric, structural and mechanical properties that favor their ability to produce horizontal ground forces at high speeds [12]. These include their larger skeletons, longer legs and therefore longer stride lengths, higher center of gravity and greater muscle and tendon stiffness [12,33,34]. These variables contribute to sex differences in mechanical sprint properties in both elite [33] and sub-elite sprinters [12]. Males obtain greater maximal force, velocity and power, have longer acceleration phases and shorter deceleration phases than females.
Moreover, if sex differences in body composition are critical in explaining the male advantage in running performance, one may expect the sex gap to be greater in disciplines that rely predominantly on muscular strength and power. However, this is not the case; the sex gap for short sprint events (100m and 200m) are typically smaller than distance events [3,5,23] (Fig. 1, Fig. 2, Table 1). A potential reason for this is that female sprinters have somewhat of an advantage due to their relatively smaller upper-body mass, meaning there is less inertia to overcome when accelerating [23].

2.1.2. Middle-distance

Middle-distance running, particularly the 800m, is an interesting and challenging field for sports physiologists to study because it represents the ‘middle ground’ between aerobic and anaerobic energy domains [35]. The estimated anaerobic energy contribution to 800m running is higher in males than females [35,36] which could be related to sex differences in muscle fiber type distribution, with male middle-distance runners displaying a greater proportion of fast twitch fibers [37,38].

Furthermore, it is recognized that elite male 800m runners possess biomechanical and neuromuscular abilities that underpin fast maximal sprinting speed (MSS), which is a requirement for competitive success [39,40]. Sandford et al. found that elite male 800m runners have a large anaerobic speed reserve (ASR) – the difference between MSS and the velocity at VO2max [39]. Possessing a large ASR may be
advantageous because it signifies the athlete has a large ‘race pace’ speed bandwidth in which they can adjust velocity to produce mid-race surges and end-kicks, as well as the force application abilities to execute very fast starting velocities [40]. The role of the ASR in female middle-distance running is an unstudied area, and it is unclear whether female 800m runners possess these characteristics that are critical for success in male running.

Hence, the physiological, biomechanical and neuromuscular profiles of a typical female middle-distance runner could mean they have greater potential to excel at longer aerobic-based events than the 800m [35,36]. If this is true, then you may expect the sex gap to be greater in the 800m than other middle- and long-distances. This was not clearly evident from the top 20 sex gap analysis; however, we did see a narrowing of the gap over time for the 1,500m and 5,000m, but this trend was absent for the 800m (Fig. 1). Perhaps females are ‘training smarter’ in these longer events, leading to greater relative improvement compared to males. With this in mind, there may be scope for female 800m runners to narrow the sex gap by tapping into the ASR domain, which is evidently a successful approach for male middle-distance runners [39]. There is a male sex bias in middle-distance running research [41 - unpublished observation from Mpholwane, Master’s thesis] which means that coaches tend to train female athletes using strategies that have been validated in males, but do not take into consideration aforementioned sex differences. Hence, more research is needed using female runners to ensure that training strategies will enable them to reach their biological potential.
It is also important to consider the large diversity in physiological and mechanical profiles of middle-distance runners [42]. Sandford et al. identified speed-based and endurance-based subtypes in male 800m runners, and asserted that both are capable of executing successful performances through adopting tactics/pacing that favor their underlying physiologies and mechanics [39]. We have observed similar subtype categorizations in female 800m runners (unpublished data). Hence, coaches and athletes should be aware of their unique profile and use this information to advise training and competition practices.

2.1.3. Long-distance

Over long-distances, the variance between sexes is primarily related to differences in maximal oxygen consumption (VO₂max). Elite male marathon runners have relative VO₂max values that are ~10% higher than their female peers [43]. This is because males have less fat mass and greater skeletal muscle mass, the most metabolically active tissue in the body, than do females [44]. Additional physiological variables likely contribute to the superior cardiorespiratory capacity in males. Males have greater red blood cell and hemoglobin concentrations than females, therefore a higher blood oxygen carrying capacity [45,46]. Additionally, males have larger hearts and lungs relative to body size [47–49], as well as larger cardiovascular preload and stroke volumes [50,51]. Since VO₂max represents the upper limits in aerobic
capacity and maximal rate of oxidative ATP production [52], it is clearly a key determinant of endurance running performance difference between the sexes [1,2].

Physiological differences related to thermoregulation [1] and metabolism [53,54] could explain some of the sex variance in long-distance running performance; although, their role is less clear. Females have greater reliance on lipid oxidation during prolonged submaximal exercise than males [53,54], and this may give them an advantage over marathon distances due to glycogen sparing and delaying fatigue [23]. In support, the average top 20 sex gap for the Marathon is typically lower than other long- and middle-distance events (Fig. 1). However, this advantage in fuel regulation may be negated in Marathon racing, where both sexes use regular carbohydrate feeding which will reduce reliance on lipid metabolism [5]. There is no conclusive evidence for sex differences in mitochondrial capacity, lactate threshold or running economy [2], which are also key determinants of endurance running performance [52].

2.2. Sex Inequality in Participation and Opportunity

The sociocultural conditions hypothesis states that sex differences in opportunities and participation explain variance between male and female sports performance (above that which is rooted in biological differences) and the lower depth of female competition [8,26]. Female participation in athletics has increased drastically since the first modern Olympic games in 1896, where not a single female competed.
Legislative changes throughout the 20th century meant that females were permitted to compete in events from which they were previously banned, for example in the Olympic 1,500m in 1972 and the Marathon in 1982 [1]. Three milestones were achieved at the London 2012 Olympic Games: 44.3% of participants were females, the highest percentage of any Summer Olympic Games; females competed in every event; all nations were represented by female athletes [17]. Title IX legislation has promoted equal opportunities for females to train and compete at the U.S. collegiate level, and has equalized the financial aid awarded to males and females within an institution [14].

Despite the progress made in legislation, policies and participation, sex inequality still pervades sport and sociocultural factors are likely to influence the sex gap today [13]. There is a discrepancy in funding and financial incentives, social support provided by governing bodies and sporting federations, and media representation between male and female athletes [13,14,17]. Alongside this, stereotypes and perceptions remain a barrier to female athletes; sport is viewed by many as a masculinized domain and despite opportunities, females are still less likely to participate than males [14].

Some have argued against the sociocultural conditions hypothesis as an explanation for the sex gap in absolute performance and competition depth. The frequency at which females set WRs in athletics decreased between 1980s – 2008, despite growing numbers of female participants at the Olympics, indicating that participation
is not a limiting factor for the progression of female performance [9]. However, this is an incomplete argument; despite roughly equal numbers of male and female Olympic competitors, females are still underrepresented at the sub-elite and grassroots level [13–15]. This could be the source of the sex gap in competitive depth at higher levels of competition. Additionally, whilst female athletes in countries such as the USA benefit from legislation promoting equal opportunities and participation in sport, this is not universal [13].

Furthermore, Keenan et al. [8] found that female collegiate rowers improved more than their male peers between 1997 – 2016, narrowing the sex gap in absolute performance and competition depth. These changes coincided with an increase in female, but not male, participation. Additionally, lower female participation is associated with an increase in the sex gap in Marathon running [25]. These examples demonstrate that participation is an important factor related to changes in female performance and the sex gap evolution, corroborating the sociocultural conditions hypothesis.

The expanding of the sex gap with rank position, an indicator of lower depth in the female field, is more apparent in the longer distances (Fig. 2). In the 5,000m, 10,000m and Marathon, there is a larger increase in the sex gap with rank, compared to the 100m and 200m (and to a lesser extent 800m and 1,500m) where the changes between 1st and 20th ranks are small. This could be because females have been competing over long-distances for a shorter time (the first Olympic
Marathon for females took place in 1984) resulting in a time lag effect. We may see an improvement in depth of long-distance running as more females have the opportunity to train and compete over time.

2.3. Competitiveness and Psychology

The evolved predispositions hypothesis argues that there are innate and evolved sex differences in competitiveness and motivation that explain the sex gap in competition depth [8,15,16]. Deaner [16] argues that males have a predisposition for enduring competitiveness, meaning they are attracted to performance-based environments where they display and compete for status. As such, males are more likely to be dedicated to the training regimens that are required for success in sport; this drives up the standard and depth of male competition. In support, Deaner found that in the USA more male high school, collegiate and professional track runners ran relatively fast compared to the sex-specific world class standards than did their females counterparts [15].

When investigating potential sex differences in the psychological disposition toward competitive environments, it is useful to analyze how male and female runners execute performance, i.e., their pacing strategy. Pacing can be described as the distribution of metabolic resources over the course of a race [55]. Female runners typically display more even pacing profiles across middle- and long-distances at the elite [56,57] and recreational level [58–61]. Male runners are more likely to adopt
risky and ambitious pacing strategies – starting too fast and slowing significantly in the second half of the race – which could reflect an overconfidence in their abilities. This is consistent with the evolved predispositions hypothesis. Conversely, Hanley and Hettinga [62] found that both sexes displayed ‘ego oriented behaviour’ in major championship 800m and 1,500m races. The eventual gold medalists ran to win during qualifying rounds, as opposed to doing just enough to qualify and preserve energy reserves for the final. Other studies demonstrate similarities in race strategies between the sexes, particularly amongst medalists [63,64]. This indicates elite female runners display equally competitive or risky racing behaviours as males; however, perhaps relatively fewer females have such a disposition at lower competitive levels.

One could integrate aspects of both the enduring competitiveness and sociocultural conditions hypotheses to explain why fewer females engage in competitive running. Perhaps males possess a greater competitive drive to pursue sporting success from a young age because they are primed by their sociocultural environment to desire/expect this. Likewise, females may anticipate fewer opportunities, less acceptance and less support, so have less motivation to engage in sport.

3. Practical Applications

Why should we be concerned with how the sex gap in elite runners is evolving or the underlying explanations? The purpose of this discussion is not to create a ‘battle of
the sexes’ [65], since males and females are not in direct competition with each other but, rather, with members of their own sex. This discussion should instead be approached with the view of seeing both male and female athletes maximize their biological potential and push the limits of human performance. If this is achieved by both sexes, the magnitude of the gap is insignificant. However, if it is apparent that one sex has more opportunities, support, incentives and provisions to reach their performance potential, we are faced with an inequality issue that should be challenged. As argued in this review, females historically and presently are the disadvantaged sex within sport.

It appears that there is scope to narrow the sex gap for elite runners, particularly in relation to competition depth. Sex gaps as low as 10 – 11% are biologically possible for the best male and female runners (Table 1), but we consistently observe increasing sex gaps at lower performance levels (Fig. 2). To address the sex gap in competitive depth, governing bodies and sporting federations should implement strategies to expand the talent pool from which the world’s best athletes are drawn. This should focus on increasing female participation in grassroots sport, improving talent identification schemes to recognize young female athletic talent, and retaining these athletes in the transition from junior to senior level competition. Media campaigns should be used to challenge the stereotypical view that sport is a masculine domain and grow commercial interest in female sport. More research in female runners is needed so that coaches and practitioners better understand the unique training responses, race demands, physiologies and mechanics of their
female athletes. Finally, financial provisions and incentives should be equalized between the sexes, particularly in countries where there are fewer policies and legislations in place that support the female athlete.

4. Conclusions

It is undeniable that the drastic narrowing of the sex gap during the 20\textsuperscript{th} century has levelled off, and performance will not be completely equalized between the sexes, at least for Olympic running distances [1,3,9]. However, the assertions that the sex gap is now fixed and explained totally by biological sex differences is an overly simplistic and limited explanation. The sex gap in athletic performance is not a stable entity; elite male and female runners are constantly evolving in relation to their same-sex competitors and to one another. In the last two decades, the top 20 sex gap has widened slightly for the 400m, narrowed slightly for the 1,500m and 5,000m, and had fluctuated for the 10,000m and Marathon (Fig. 1). This could be due to a range of integrated biological and environmental factors; shifts in training strategies, technologies, research, event demands, opportunities, participation, provisions, legislation and perceptions can all play a role in performance progression in runners. When one sex experiences differential advantages from these factors, this is likely to be reflected in a change - narrowing or widening - in the sex gap. The present review demonstrates that there is not just a sex gap in absolute performance, but also in competition depth. The sex gap increases with rank position, i.e., at a lower performance level, in events 400m and longer (Fig. 2). This suggests there are more
male runners that are closer to the sex-specific world class standard than females, and that the male competitive field is more homogenous. Seeking to rectify this gap will require a multidisciplinary approach to address the sex biases that pervade sport and research.
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CHAPTER 3

Research Manuscript

This chapter presents a research manuscript written for submission to the *Science & Sports* Journal, titled “The Role of the Anaerobic Speed Reserve in Female Middle-Distance Running”. The references cited in this review are provided at the end of the chapter and follow the standards set by the *Vancouver Convention* as per the journal specification. Tables and figures are embedded in the text. This research manuscript is authored by Lydia Hallam, Jeremy Ducharme, Zachary Mang and Fabiano Amorim.
Title: The Role of the Anaerobic Speed Reserve in Female Middle-Distance Running
Titre: Le rôle de la réserve de vitesse anaérobie dans la course de demi-fond féminine

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The Role of the Anaerobic Speed Reserve in Female Middle-Distance Running

Le rôle de la réserve de vitesse anaérobie dans la course de demi-fond féminine

Summary

Objectives: Middle-distance running represents a complex interplay of metabolic and mechanical factors. A better understanding of the requirements of male 800m running has been proposed using the Anaerobic Speed Reserve construct. However, the Anaerobic Speed Reserve is yet to be investigated within female middle-distance running.

Methods: The Anaerobic Speed Reserve, defined as the difference between maximal sprint speed and maximal aerobic speed, was assessed in 12 sub-elite female middle-distance runners using fastest 15m sprint times and a maximal incremental treadmill test, respectively. Participants were allocated to either 400–800m or 800m–Mile sub-groups. Comparisons between groups were made for Anaerobic Speed Reserve, maximal sprint speed, maximal aerobic speed and the speed reserve ratio, defined as maximal sprint speed divided by maximal aerobic speed. The relationships between the Anaerobic Speed Reserve components and 800m season’s best race times were assessed.

Results: Female 400–800m middle-distance runners had a significantly larger Anaerobic Speed Reserve ($p=0.013$), faster maximal sprint speed ($p=0.001$) and greater speed reserve ratio ($p=0.042$) than runners in the 800m–Mile group. There was a significant negative correlation between maximal aerobic speed and 800m time ($p=0.012$), but no statistically significant relationship was observed for Anaerobic Speed Reserve ($p=0.900$), speed reserve ratio ($p=0.558$) or maximal sprint speed ($p=0.057$).

Conclusions: Female middle-distance sub-groups can be distinguished using the speed reserve ratio, with implications for coaches and physiologists to use the speed reserve ratio as a tool to characterize athletes and advise individualized training prescription. Aerobic power appears to underpin female 800m performance as opposed to anaerobic or sprint abilities in these sub-elite athletes.

Keywords: maximal sprint speed, maximal aerobic speed, biomechanics, physical performance

Résumé

Objectifs: La course de demi-fond représente une interaction complexe de facteurs métaboliques et mécaniques. Une meilleure compréhension des exigences de la course à pied de 800m hommes a été proposée en utilisant le concept de réserve de vitesse anaérobie. Cependant, la réserve de vitesse anaérobie n’a pas encore été étudiée dans la course de demi-fond féminine.
Méthodes: La réserve de vitesse anaérobie, définie comme la différence entre la vitesse maximale de sprint et la vitesse aérobie maximale, a été évaluée chez 12 coureuses de demi-fond féminines sous-élite en utilisant respectivement les temps de sprint les plus rapides de 15m et un test incrémental maximal sur tapis roulant. Les participants ont été répartis entre des sous-groupes de 400–800m ou de 800–Mile. Des comparaisons entre les groupes ont été faites pour la réserve de vitesse anaérobie, la vitesse maximale de sprint, la vitesse aérobie maximale et le ratio de réserve de vitesse, défini comme la vitesse maximale de sprint divisée par la vitesse aérobie maximale. Les relations entre les composants de la réserve de vitesse anaérobie et les meilleurs temps de course de la saison sur 800m ont été évaluées.

Résultats: Les coureuses de demi-fond féminines de 400–800m avaient une réserve de vitesse anaérobie significativement plus grande ($p = 0.013$), une vitesse de sprint maximale plus rapide ($p = 0.001$) et un rapport de réserve de vitesse plus élevé ($p = 0.042$) que les coureurs du groupe 800–Mile. Il y avait une corrélation négative significative entre la vitesse aérobie maximale et le temps de 800m ($p = 0.012$), mais aucune relation statistiquement significative n’a été observée pour la réserve de vitesse anaérobie ($p = 0.900$), le ratio de réserve de vitesse ($p = 0.558$) ou la vitesse maximale de sprint ($p = 0.057$).

Conclusions: Les sous-groupes féminins de demi-fond peuvent être distingués en utilisant le ratio de réserve de vitesse, avec des implications pour les entraîneurs et les physiologistes d’utiliser le ratio de réserve de vitesse comme un outil pour caractériser les athlètes et conseiller une prescription d’entrainement individualisée. La puissance aérobie semble sous-tendre la performance féminine sur 800m par opposition aux capacités anaérobies ou de sprint chez ces athlètes sous-élites.

Mots clés: vitesse maximale de sprint, vitesse aérobie maximale, biomécanique, performance physique
1. Introduction

Middle-distance running events, including the 800m, 1,500m and Mile, rely on simultaneous contributions of aerobic and anaerobic energy systems, as well as neuromuscular (e.g., strength and coordination) and mechanical (e.g., stride length and frequency) factors [1, 2]. Middle-distance runners display heterogenous physiological profiles [3], and there is large inter-individuality in aerobic energy contribution to 800m running which is estimated between ~60–75% [4, 5]. It is suggested that runners possessing a large anaerobic capacity and speed ability could compensate for a lower maximal oxygen consumption (VO$_2$max) [6], indicating physiological diversity between individuals with similar performances [7].

Whilst the aerobic determinants of middle-distance running have been well described [8–11], quantifying anaerobic energy contribution and the relationship between anaerobic metabolic capacity and middle-distance performance remains unclear [7, 12–14]. Furthermore, little is known about the neuromuscular and mechanical requirements [15]. Sprint ability is a technical variable limited by force application and mechanics, as opposed to anaerobic energy supply [13] which has been related to male 800m performance [16, 17]. Moreover, speed application is considered a skill involving technical adjustments of stride length and frequency, allowing for smooth speed transitions at minimal energetic cost [2]. There is a need to characterize the performance variables that are important within middle-distance running.
The Anaerobic Speed Reserve (ASR) is a novel concept within the field of middle-distance running performance [17]; ASR is defined as the speed range between maximal aerobic speed (MAS - the minimal speed required to elicit VO$_2$max, or vVO$_2$max [18]) and maximal sprint speed (MSS - top end speed) [12, 19, 20]. Since middle-distance races lasting ~1.5–5 minutes are run at velocities within this speed bandwidth, i.e., above vVO$_2$max, the ASR could provide a framework to understand the physiological, mechanical and neuromuscular profiles of middle-distance runners [15].

Sandford et al. [17] found that possessing a larger ASR, as a function of faster MSS, is a key factor that differentiates elite male 800m performers. In theory, for the same absolute running velocity above VO$_2$max, an athlete with a faster MSS will be working at a lower portion of their ASR; this represents a lower physiological load compared to an athlete with a smaller ASR and slower MSS [20]. Additionally, a runner with a large ASR has a greater speed range within which to adjust velocity and cope with the high speed requirements of the 800m race [21]. This has implications for executing a ‘finishing kick’ in the 1,500m and longer events [2, 22, 23].

Sandford et al. [17] suggested that the ASR can highlight the physiological and mechanical diversity of male 800m runners. The speed reserve ratio (SRR), calculated as MSS divided by MAS, summarizes the ASR characteristics of an
athlete within a single value, and can distinguish between male 800m sub-groups. 400–800m runners have the largest SRR, followed by 800m specialists and then 800–1,500m runners. Likewise, a previous investigation using a small sample of female runners (n=3) was able to assign similar sub-groups using ASR characteristics [15]. Since MAS is primarily determined by metabolic factors, whilst MSS is a product of ground force characteristics, the ASR and SRR can provide insight into an athlete’s metabolic and mechanical strengths and limitations, and aid classification of middle-distance runners into sub-groups [2, 15].

To date, limited data have been published on ASR in female middle-distance runners [15]. It is unclear if the ASR is an important component of female middle-distance running. The metabolic demands of middle-distance running are different between male and female athletes, with the estimated anaerobic energy contribution over 800m being higher in males [5]. Based on this observation, it could be assumed that possessing a large speed reserve is less important for female middle-distance runners. Nonetheless, Yoshida et al. found a significant correlation between female 800m performance and external power output [8], implying the anaerobic component is critical for performance. More research is needed to determine the importance of the ASR and MSS in middle-distance running in females. Therefore, the purpose of this study was to determine whether the SRR and ASR components are different between female middle-distance running sub-groups. Secondly, we sought to investigate the relationship between female 800m race performance and the ASR, as well as MAS and MSS.
2. Methods

2.1. Study Design

This was an observational study that assessed the ASR, SRR and 800m race performance of female middle-distance runners. Athletes were tested for anthropometric variables followed by a MAS assessment at the University of New Mexico (UNM) Exercise Physiology Laboratory. Within 7 days, athletes were tested for MSS at the UNM Athletics Track. Race performance data was collected over the 2020 Indoor Track and Field season (January–March). Races took place at an elevation of ~1,600m and were within 12 weeks of the initial assessment.

2.2. Participants

Participants were healthy female runners aged 18 to 25 years, who raced competitively for at least six years and were currently competing in track events. They were required to compete in at least one 800m race plus an additional race over one of the following distances: 400m, 600m, Mile, 3,000m. At the start of the study we asked participants what event(s) was the focus of their training regimen. Participants were living at an altitude of ~1,600m for at least five of the six months prior to initial assessment. All participants provided written informed consent to take
part in the study as was approved by the UNM Institutional Review Board (1521937-3).

2.3. Anthropometric Measurements

Participants completed a health history questionnaire, and height, body mass and body composition assessments. Skinfold thickness was measured at three sites (triceps, suprailiac and thigh) using a skinfold caliper (Lange Skinfold Caliper, Beta Technology Inc., Santa Cruz, CA, USA) and used to estimate body density [24], which was converted to body fat percentage (%BF) using an equation for endurance trained females [25].

2.4. Maximal Aerobic Speed Assessment

To determine the MAS, or v\(\text{VO}_2\)max, participants completed a maximal incremental treadmill test to volitional exhaustion. Initially a self-paced warm-up was performed on the treadmill, followed by a familiarization trial consisting of 1–3 minutes of moderate intensity running. After, participants wore an upper body harness (Vario Chest Harness, Black Diamond Equipment, Salt Lake City, UT, USA), attached to the ceiling through a rope to prevent falling off the treadmill at maximal effort. The MAS protocol consisted of running on the treadmill (Precor® C966, Woodinville, WA, USA) at a fixed 1% gradient with speed increasing 0.3 mph every 30 seconds until maximal exertion. The starting speed was selected on an individual basis, with the
aim of the participant reaching maximal exertion between 8 to 12 minutes of running [26]. Heart rate was recorded using a heart rate monitor and chest strap (Polar V800, Polar Electro, Kempele, Finland). Breath-by-breath pulmonary gas exchange and ventilation were measured continuously using a metabolic cart (TrueOne 2400, Parvo Medics Inc., Sandy, UT, USA), which was calibrated according to manufacturer guidelines prior to each test. Subjects wore a nose clip and were required to breathe through a Hans Rudolph mouthpiece (Hans Rudolph Inc., Kansas City, MO, USA).

The MAS/vVO$_2$max was determined using the lowest treadmill running velocity to elicit VO$_2$peak [18]. The VO$_2$peak was established as the peak 11-breath rolling average VO$_2$. To confirm VO$_2$max was met, the processed VO$_2$ data was assessed for a VO$_2$ plateau, whereby the change in VO$_2$ was ≤150 ml in the last 30 seconds of the test (adapted from Taylor et al. [27] and Yoon et al. [26]). We used the following secondary criteria to confirm that VO$_2$max was met: respiratory exchange ratio > 1.10 [28], rating of perceived exertion > 17 [29], heart rate within 10 bpm of age predicted maximum heart rate [28]. Participants were considered to have achieved VO$_2$max if 3 of the 4 above criteria were met, including a VO$_2$ plateau. If the VO$_2$peak occurred within the first 5 seconds of a stage the MAS was taken as the treadmill speed of the previous stage.

2.5. Maximal Sprint Speed Assessment
Participants completed a warm-up which included 20–30 minutes of jogging, light dynamic stretching and short sprints on an outdoor all-weather track. Participants then performed one practice 45m sprint and three trial 45m sprints at maximal effort, off a rolling start of 20–30m in length. Participants wore running flats or spikes.

An electronic timing system was used to measure the time to cover each 15m section of the 45m sprint (Freelap Pro BT424, Freelap USA, Pleasanton CA, USA). This system required participants to wear a small timing chip (FxChip BLE) clipped onto their waistband. The time it took the participants to run between timing cones (Tx Junior Pro transmitters) set 15m apart was transmitted to a smartphone via Bluetooth. The participants’ fastest 15m segment time across all trials was converted to km/h, and used as an estimation of MSS. A rest interval of ~3 minutes was taken between each sprint trial. Measurements of wind speed (AR816 Anemometer, Smart Sensor®, Dongguan, China) and temperature (Sling Psychrometer MA-164, Gilson Company Inc., Lewis Center, OH, USA) were taken during each assessment.

2.6. Anaerobic Speed Reserve and Speed Reserve Ratio

The ASR was calculated using the following equation for each participant:

\[ \text{ASR (km/hr)} = \text{MSS (km/hr)} - \text{MAS (km/hr)} \]

The SRR was calculated as follows:

\[ \text{SRR} = \frac{\text{MSS (km/hr)}}{\text{MAS (km/hr)}} \]
2.7. Competition Performance Data

We asked participants to notify the research team members of all track races they completed within this period over the following distances: 400m, 600m, 800m, Mile, 3,000m. Season’s best (SB) racing times were obtained from result databases that are publicly available online.

2.8. Statistical Analysis

For statistical analyses, participants were assigned to one of two groups: 400–800m or 800m–Mile. The criteria for assignment included competition distance and training history. Participants who competed in track races 800m and shorter during the current season and/or whose training regimens were targeted towards preparation for these shorter middle-distance events were placed in the 400–800m group. Likewise, those competing in events 800m and longer and/or whose training was directed towards preparation for these events were placed in the 800m–Mile group.

All data were analyzed using GraphPad Prism 8 (San Diego, CA, USA). Data are presented as mean ± standard deviation. A Shapiro-Wilk test was used to assess the data for normality. Statistical significance was set at $p < 0.05$. Separate independent sample $t$-tests were conducted to compare group differences in descriptive variables (age, height, body mass, %BF, years running experience).
ASR, MSS, MAS, SRR, VO\textsubscript{2max} and SB 800m time. Cohen’s $d$ effect size (ES) was calculated for group differences, classified as small ($\geq 0.2$), moderate ($\geq 0.5$) and large ($\geq 0.8$) [30]. Relationships between SB 800m time and the ASR, MSS, MAS, SRR and VO\textsubscript{2max} were determined using the Pearson correlation coefficient.

3. Results

Twelve female middle-distance runners completed the study. Five participants were assigned to the 400–800m group and seven to the 800m–Mile group. Participant information is displayed in Table 1. The 800m–Mile runners were significantly older than 400–800m runners ($p=0.033$); however, their years of running experience were similar ($p=0.564$).

During the assessment of MAS, all participants obtained a VO\textsubscript{2max}. Tail wind speed was $0.4 \pm 0.3$ m/s (range 0 to 0.8 m/s) and temperature was $11.7 \pm 7.5$ °C (range 2 to 22 °C) during MSS assessments.
Table 1. Descriptive characteristics of female middle-distance runners classified into sub-groups (mean ± SD) N=12.

<table>
<thead>
<tr>
<th></th>
<th>400–800m (n=5)</th>
<th>800m–Mile (n=7)</th>
<th>p-value</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>19.2 ± 1.1</td>
<td>21.7 ± 2.1*</td>
<td>0.033</td>
<td>1.59</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>165.4 ± 5.6</td>
<td>170.4 ± 5.0</td>
<td>0.134</td>
<td>0.94</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>55.5 ± 3.5</td>
<td>57.4 ± 5.5</td>
<td>0.498</td>
<td>0.44</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>14.3 ± 2.2</td>
<td>15.4 ± 4.3</td>
<td>0.644</td>
<td>0.32</td>
</tr>
<tr>
<td>Running experience (years)</td>
<td>8.0 ± 1.4</td>
<td>8.7 ± 2.7</td>
<td>0.564</td>
<td>0.35</td>
</tr>
</tbody>
</table>

* p < 0.05 significantly different from 400–800m sub-group

3.1. Sub-Group Analysis: ASR Components

The analysis revealed that 400–800m runners had a significantly greater ASR (p=0.013) and faster MSS (p=0.001) than runners in the 800m–Mile group (Table 2). The SRR was also significantly larger in the 400–800m group (p=0.042). There were no significant group differences for MAS (p=0.665).
Table 2. Performance variables of female middle-distance runners classified into sub-groups (mean ± SD) N=12.

<table>
<thead>
<tr>
<th></th>
<th>400–800m (n=5)</th>
<th>800m–Mile (n=7)</th>
<th>p-value</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASR (km/hr)</td>
<td>13.21 ± 2.58</td>
<td>9.70 ± 1.46*</td>
<td>0.013</td>
<td>1.73</td>
</tr>
<tr>
<td>MSS (km/hr)</td>
<td>30.58 ± 1.17</td>
<td>27.50 ± 1.19*</td>
<td>0.001</td>
<td>2.60</td>
</tr>
<tr>
<td>MAS (km/hr)</td>
<td>17.38 ± 1.84</td>
<td>17.79 ± 1.40</td>
<td>0.665</td>
<td>0.26</td>
</tr>
<tr>
<td>SRR</td>
<td>1.77 ± 0.22</td>
<td>1.55 ± 0.11*</td>
<td>0.042</td>
<td>1.34</td>
</tr>
<tr>
<td>VO₂max (ml/kg/min)</td>
<td>55.33 ± 4.68</td>
<td>56.48 ± 3.62</td>
<td>0.639</td>
<td>0.28</td>
</tr>
<tr>
<td>800m SB time</td>
<td>02:13.42</td>
<td>02:22.63</td>
<td>0.229</td>
<td>1.15</td>
</tr>
<tr>
<td>(min:sec.ms)²</td>
<td>± 00:04.49 (n=3)</td>
<td>± 00:11.52</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ASR = Anaerobic Speed Reserve; MSS = Maximal Sprint Speed; MAS = Maximal Aerobic Speed; SRR = Speed Reserve Ratio (MSS/MAS); SB = season's best.
* p < 0.05 significantly different from 400–800m sub-group
² Only 3 athletes in the 400–800m sub-group were able to complete an 800m race due to the impact of the COVID-19 pandemic on the cancellation of track competitions.

3.2. Correlations: 800m Race Performance

Two subjects (in the 400–800m group) were unable to complete an 800m race due to the cancellation of track competitions, and thus were excluded from the correlational analysis. We observed no significant relationship between 800m time and ASR (p=0.900) or SRR (p=0.558). There was a significant negative correlation between 800m time and the MAS (p=0.012) and VO₂max (p=0.010). Another
negative relationship was observed between 800m time and MSS that neared statistical significance ($p=0.057$, Figure 1).

![Graphs showing relationships between 800m time and performance metrics.](image)

**Figure 1.** Relationship between season’s best 800m performance time and a) Anaerobic Speed Reserve, b) Speed Reserve Ratio, c) Maximal Sprint Speed and d) Maximal Aerobic Speed in female middle-distance runners (n=10). The Pearson’s correlation coefficient (r), R squared value and p-values are displayed, and data are fitted with a simple linear regression line. Statistical significance was set at $p < 0.05$.

### 4. Discussion

The present study investigated whether the SRR and ASR components were different between female middle-distance running sub-groups. Our results indicate that 400–800m runners had a significantly larger ASR and SRR and faster MSS than 800m–Mile runners. A second objective was to see if the relationship between the ASR and 800m performance previously reported in male runners [17] would be
replicated in females. We did not observe a significant relationship between ASR or SRR and 800m performance time in females; however, we did see a significant negative relationship with MAS, and the relationship with MSS neared statistical significance.

The sub-group differences in the ASR, SRR and MSS are in line with the findings of Sandford et al. in elite male 800m runners [17], and a small sample (n=3) of individual female data [15]. Our findings highlight the diversity of athlete profiles in female 800m running and reveal the different ASR characteristics of 400–800m ‘speed’ types compared to 800m–Mile ‘endurance’ types. These characteristics could be explained by metabolic factors. For females, the estimated anaerobic energy contribution ranges from 20% to 41% between individuals during 800m running [5]. Such diversity in energetics could be underpinned by structural variances at the muscle fiber level [15]. Middle-distance runners possess a blend of oxidative, fatigue resistant type I muscle fibers and glycolytic, force producing type IIa and IIx fibers [31]. A large range in relative proportions of type I fibers (44.0–73.3%) have been observed in female middle-distance runners [31]. As such, 400–800m runners may execute 800m performance through greater reliance on anaerobic energy sources [7] and high mechanical power outputs [1] supported by a more glycolytic fiber type profile, whereas 800m–Mile runners may have superior aerobic capacities [3] and a predominance of oxidative muscle fibers. Our observations of a larger ASR and faster MSS with the 400–800m group support this conclusion.
The faster MSS in female 400–800m runners compared to 800m–Mile runners could be explained by neuromuscular/mechanical variations, since MSS is limited by musculoskeletal mechanics as opposed to anaerobic chemical energy supply [13]. Previously, it was suggested that differences in muscle mass could account for the observed variance in MSS ability amongst male 800m runners [17]. We did not observe differences in body mass or %BF between our two groups of female 800m runners, implying that greater muscle mass does not explain the faster MSS in the 400–800m runners. Though larger muscle volume will optimize ground force application, other mechanical components are important in MSS ability. For example, variances in kinematic variables such as ground contact time, knee range of motion and stride length, exist between sprinters, middle-distance and long-distance runners [32]. This implies that differences in sprint ability between event groups are underpinned by technical factors. As such, the 400–800m runners in this study may possess the technical abilities to optimize force production over short contact times [1], increasing impulse and thus MSS.

Contrary to observations in male 800m athletes [17], MAS was not greater in 800–Mile runners compared to 400–800m runners in this study. The MAS, or vVO₂max, represents an interplay between VO₂max and running economy [33]. Sandford et al. observed MAS differences between 800m male sub-groups, albeit not as large as MSS differences [17]. Perhaps the elite athletes used in Sandford et al.’s sample were more divergent in their physiological profiles due to more years training and/or
more rigorous training stimulus compared to the athletes in the present study. Notwithstanding, Sandford and Stellingwerff suggest using three indicators when profiling runners to present a full picture of their metabolic and mechanical characteristics [15]: velocity at onset of blood lactate accumulation (v4mmol lactate), MAS and MSS. As such, variables not measured in this study including v4mmol may have been superior in the 800m–Mile runners.

We found that for females, a fast MAS was related to a faster 800m time, whereas a large ASR and SRR was not, contrary to findings in elite males [17]. This suggests the key predictors of performance between our female sample and the elite male sample in the Sandford et al. study are dissimilar, which could reflect sex-differences in the physiological demands of 800m running. Duffield et al. found that average estimated anaerobic energy contributions were lower in females (~30%) compared to males (~40%) during 800m running [5]. This could reflect the larger muscle mass [14] and greater percentage of type IIa/x fibers [31] in males. Additionally, the sex differences in 800m energetics could be because males run at faster absolute speeds and for shorter durations, meaning their anaerobic contribution is greater than in females competing over the same distance [5]. From this perspective, it could be considered that having a larger ASR is more important in male 800m running. Moreover, Sandford et al. [17] studied a homogenous elite male population (800m SB range 1:44.50–1:47.36), whereas the present study was conducted in non-elite female athletes who were more heterogenous in performance level (800m SB range 2:09.20–2:41.50). Aerobic variables can effectively differentiate sub-elite
runners; however, once a given aerobic standard is reached, a large ASR and fast MSS becomes more pertinent at separating performers [2, 17]. This is supported by our study and others who found significant negative correlations between MAS and 800m time in sub-elite runners [10, 11]. We also observed a significant negative correlation between VO$_2$max and 800m performance (p=0.010); VO$_2$max can predict performance in heterogenous running populations, but less so in runners with similar VO$_2$max values as expected at the elite level [9]. This means that key predictors of performance are different between well-trained and elite athletes.

Sandford et al. found that a fast MSS and large ASR are significant factors in distinguishing between elite male 800m performers [17], and whilst the ASR does not relate to performance in our female sample, the negative relationship between 800m time and MSS may have reached statistical significance with a larger sample (p=0.057, 1-β=0.65). When assessing sex-differences in the physical determinants of 800m running and the role of the ASR, one should consider differences in pacing strategies that influence the metabolic and mechanical demands of running. Within championship racing the pacing strategies of males and females are identical, with both sexes displaying characteristic ‘seahorse-shape’ pacing [34]. Interestingly, females run their first 100m at a pace relatively quicker than men [34]. Though this may not apply to the sub-elite population in the present study, there are implications that at an elite level, both males and females require a large anaerobic capacity and mechanical abilities to cope with the velocity requirements of 800m races. Thus, the importance of a large ASR in female 800m running is not undermined; replication of
this study within an elite female population is warranted to elucidate the role of the ASR in middle-distance performance compared to males.

4.1. Limitations

The authors acknowledge that we only made comparisons between two 800m sub-groups (400–800m and 800–Mile) due to sample size limitations. However, it is expected that females can be categorized into one of the three sub-groups identified in male middle-distance runners (400–800m, 800m specialist, 800–1,500m) [17].

The validity of the methodologies used in the present study should be considered. This study employed a novel protocol to assess MAS/vVO$_2$max, using 30-second stages to allow for precise identification of the minimum velocity to elicit VO$_2$max [18]. A vVO$_2$max protocol is inappropriate if it does not allow a true VO$_2$max to be achieved [35]. All participants achieved a VO$_2$ plateau and at least 3 of the 4 criteria to confirm attainment of VO$_2$max. This suggests the protocol was sufficient to allow a true VO$_2$max and determine vVO$_2$max.

To our knowledge, this was the first research study to use the Freelap electronic timing system and validation of this device is warranted. MSS assessment took place in an open environment where temperature and wind speed were not controlled, which may have affected the results.
5. Practical Applications

Whilst a large ASR does not automatically determine success within middle-distance running, the ASR construct indicates the speed bandwidth of an athlete within which race velocities lie. This has implications for understanding an athlete's physiological and mechanical strengths/limitations and optimization of race strategies [2, 17]. Profiling using the SRR could be used by sports physiologists and coaches to characterize middle-distance runners into sub-groups, advise individualized training to improve MSS and MAS and equip the athlete for their event demands, and to assess adaptations over time. Whilst we used a laboratory method to directly assess MAS, a validated regression equation for field prediction of MAS using 1,500m performance time exists as a practical tool for coaches who don’t have access to metabolic cart and treadmill [36]. MSS could also be measured in the field using electronic timing systems or hand-timing.

6. Conclusions

We demonstrated that 400–800m female runners have a larger ASR and SRR and faster MSS than 800m–Mile runners. This adds to the existing literature on how the ASR construct can illustrate the physiological and mechanical diversity within male middle-distance running [17]. We found a significant relationship between MAS and 800m performance, highlighting the importance of aerobic capacity in distinguishing between female runners in this sub-elite, heterogenous sample. Nonetheless, the
relationship between MSS and female 800m performance neared statistical significance, and there is reason to believe that anaerobic capacity and sprint ability, and by extension a large ASR, is important in female middle-distance. More research is needed in an elite population to explore the role of the ASR in female middle-distance performance.

Disclosure of Interest

The authors declare that they have no competing interest.

Acknowledgments

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References


CHAPTER 4

Summary, Conclusions and Recommendations

Summary

1. Review Manuscript
The review manuscript titled “Expanding the Gap: An Updated Look into Sex Differences in Running Performance” provided a summary of the current literature on the sex gap in running performance and gave updated insights into the top 20 sex gap for the Olympic running disciplines 100m to Marathon distance over the past two decades. The manuscript confirmed previous findings of increases in the sex gap at lower performance levels, indicating a sex gap in competitive depth. Consideration was given to various biological and environmental explanations for the sex gap in athletic performance.

2. Research Manuscript
The research manuscript titled “The Role of the Anaerobic Speed Reserve in Female Middle-Distance Running” provided data to contribute the small yet growing body of literature on the ASR and its relation to running performance (Bellinger et al., 2020; Sandford et al., 2018; Sandford et al., 2019b; Sandford et al., 2019c; Sandford & Stellingwerff, 2019). This was the first study to focus specifically on the role of the ASR in sub-elite female middle-distance runners. The present findings revealed diversity in the physical profiles of female 800m runners; these were demonstrated by differences in ASR, SRR and MSS. Additionally, the study showed that indices of aerobic capacity – MAS and VO$_2$ max – were the primary predictors of 800m
performance in this sub-elite female cohort, distinguishing this population from elite male middle-distance runners (Sandford et al., 2018).

Conclusions

The primary conclusions gained from this thesis are as follows:

1. The ASR construct can be used to illustrate the physiological and mechanical diversity within female middle-distance running and allow 800m runners to be separated into sub-groups: female 400–800m runners have a larger ASR and SRR and faster MSS than 800m–Mile runners.

2. In a heterogeneous sample of sub-elite female 800m runners, the key predictors of performance were measures of aerobic capacity; the MAS and VO$_2$max had a significant relationship with 800m performance time.

3. The ASR is not correlated to 800m performance in sub-elite female middle-distance runners, hence a large ASR does not always indicate superior running abilities.

4. There are small changes and fluctuations in the sex gap evolution for Olympic running disciplines, indicating that the sex gap in athletics is not ‘fixed’ per se.

5. There are a range of biological and environmental factors that could contribute to the sex gap in absolute running performance and competition depth.

6. The sex gap is wider when using the top 20 annual performances compared to world record performances, and the sex gap increases with world ranking.
This indicates lower depth in female running compared to males, particularly in events 400m and longer.

**Recommendations**

1. There should be more attention given to understanding the unique requirements of female athletic performance, including within middle-distance running. Biological sex differences mean that females may have different responses to training interventions than their male peers. Furthermore, the physical, tactical and behavioral demands of races may differ between the sexes. In order to support female athletes to reach their biological potential in running performance, these sex differences must be studied, understood and addressed by the athletic community which includes researchers, coaches and sports practitioners.

2. Research is needed into the role of the Anaerobic Speed Reserve in elite female middle-distance runners. It is still unclear whether a large ASR and fast MSS are critical determinants of performance in elite female 800m as has been previously confirmed in males (Sandford et al., 2018). This will inform coaches of the training practices that need to be adopted by elite female middle-distance runners in order to maximize success in their sport.

3. Greater appreciation should be had for the physiological and mechanical diversity between athletes, particularly within middle-distance running. Two athletes can have very different profiles yet execute equally optimal performances through understanding their strengths and weaknesses and
applying this knowledge to training and competition. Coaches should not adopt a ‘one size fits all’ approach to training their athletes, and instead adapt training protocols around each athlete’s unique profile and their event demands. Athlete profiling using the ASR and SRR is a relatively simple and effective way to get ‘first layer’ information about the metabolic and mechanical properties of a runner, i.e., if they are speed-based or endurance-based athletes. This involves prediction of MAS using 1,500m race or time trial time (Sandford et al., 2019c) and field measurements of MSS on an Athletics Track for the calculation of SRR (SRR = MSS/MAS). These measures can also be used to track changes in an athlete’s profile over time, for example to assess their responsiveness to training.

4. Part of the sex gap in running performance can be explained by non-biological influences including sex differences in opportunities, provisions, incentives and media representation in sport, as well as stereotypes and biases. It is apparent that females are the disadvantaged sex in the domain of sport, including within running. These sociocultural factors could explain part of the sex gap in competition depth, i.e., that more males run closer to sex-specific world class standards than females, and male runners have more homogenous competitive fields. There is scope to close this sex gap through interventions that promote increased engagement in running at all levels of competition (grassroots, recreational, sub-elite and elite) and encourage elite female athletes to reach the biological limits of performance. This will require a multidisciplinary approach through the work of researchers, sports
practitioners, coaches, psychologists, policy makers, sporting governing bodies and federations and the media.
APPENDICES

A. Informed Consent

B. Health History Questionnaire

C. Data Collection Sheet
APPENDIX A

Investigating the Role of the Anaerobic Speed Reserve in Male and Female Running Performance

Consent to Participate in Research
12/09/2019

Purpose of the study: You are being asked to participate in a research project that is being conducted by Dr. Fabiano Amorim and associates from the department of Health, Exercise and Sports Sciences. The purpose of this research is to investigate the role of the anaerobic speed reserve (ASR) in middle- and long-distance running performance. The ASR, defined as the difference between an individual’s maximal aerobic speed (MAS) and maximal sprint speed (MSS), has been correlated with male 800m racing performance. There is little research investigating the role of the ASR in other running events, and no studies on this topic have compared males and females. We hope to better understand the metabolic and mechanical demands of middle- and long-distance running through this study, which could help the sports physiologist, coach and athletes in the development of effective training programs. You are being asked to join this study because you are a track and field athlete who will be racing over the 2020 Track and Field season.

This consent form contains important information about this project and what to expect if you decide to participate. Please consider the information carefully. Feel free to ask questions before making your decision whether to participate. Your participation in this research is voluntary.

Key information for you to consider:
- Visit 1: Informed Consent, Blood Pressure, Height, Weight, Body Composition Assessment, VO₂max Test
- Visit 2: Meter Maximal Sprint Speed Test
- Race Information: Data regarding your season’s best racing times over the 2020 Track and Field season will be collected.
- Participation in this project will last the duration of the Track and Field 2020 season.
  - Visit 1 will take up to 1 hour.
  - Visit 2 will take up to 1 hour.
  - Competition schedules will vary per athlete, the 2020 season may last up to 12 weeks.
- Major Benefits:
  - Participants will receive results and interpretation of their maximal aerobic speed and maximal sprint speed assessments.
- Major Risks:
  - General exercise side effects: muscle soreness, fatigue, nausea, or dizziness during or after the session.
  - Risks of VO₂max testing: incidence of fatal and nonfatal events are very low, ~ 1 per 10,000 hours of testing. Risk of injury during the test is reduced through use of an upper body harness.
What you will do in the study:

The study will require a total of two visits, one to the Exercise Physiology Laboratory (Johnson gym, B143) and one to the University of New Mexico Athletics Track. You will be required to complete at least one race over at least one of the following distances: 400m, 800m, 1500m/mile, 3000m, 5000m, over the course of the 2020 Track and Field season.

Visit 1: Informed Consent, Blood Pressure, Height, Weight, Body Composition Assessment, VO$_{2\text{max}}$ Test:

You will come to the Exercise Physiology Laboratory to meet with the researchers after having read this consent form. More information about the study, including criteria that may exclude you from the study, what is expected of you, and what is required for the study is explained in detail below. You will have the opportunity to speak to the research team members about any questions you have regarding the study.

- If you are still interested, you will then sign this consent form. You may still be excluded from the study after signing the consent form depending on your answers to the questionnaires (described below) and testing we will do.
- You will fill out questionnaires about your health and your exercise regimen.
- After reviewing the questionnaires and discussing any health concerns you have about joining the study, one of the research team members will let you know whether you qualify to continue.
- We will measure your blood pressure whilst you are seated and have rested at least 5 minutes. If your blood pressure is higher than 140 mmHg (top number) and/or 90 mmHg (bottom number) taken twice by our staff, we will not be able to enroll you in the study.
- If you are a woman of childbearing potential, you will be asked to do a urine pregnancy test in a private restroom. You will be able to see the results of the test. If you are pregnant, we cannot enroll you in the study and we will suggest you see your health care provider for more precise testing.
- You will be asked to provide a recent blood test report (within 1 month) detailing ferritin levels.
- If you qualify for the study, we will measure and record your height and weight without shoes.
- We will assess your body composition using the skinfold method. A research team member trained in administering skinfold tests will use calipers to measure your skinfold thickness at three sites (chest, abdomen and thigh for men and triceps, hip and thigh for women).
- You will be required to follow certain guidelines in order to be able to complete the exercise testing. These will include drinking plenty of water, having no caffeine (coffee, caffeinated sodas, etc.) for at least 4 hours, no exercise for at least 12 hours and no alcohol for at least 24 hours before you arrive.

Maximal Aerobic Speed Assessment: VO$_{2\text{max}}$ Test

Your VO$_{2\text{max}}$ refers to the maximum amount of oxygen you can utilize during maximal exercise which is generally considered the best indicator of cardiovascular fitness. We are interested in finding your running velocity at VO$_{2\text{max}}$ (vVO$_{2\text{max}}$) in order to determine maximal aerobic speed. The procedure for this assessment is described below.
• You will complete a self-paced warm-up on the treadmill in the laboratory.
• This will be followed by a familiarization trial, if required based on your previous experience, consisting of 5 minutes of moderate intensity exercise on the treadmill whilst wearing the mask and nose clip required for the experimental trial.
• You will then perform a maximal incremental treadmill test to determine the $\text{vVO}_2\text{max}$. This will require you to wear a mouthpiece, nose clip and heart rate monitor. You will run on the treadmill at a fixed 1% gradient. Treadmill speed will begin at a relatively slow pace and will be increased every 30 seconds until you reach maximal exertion. When you feel you cannot run any longer, you will sign to the researcher to stop the treadmill or will press the emergency stop button yourself. The test typically takes 8 – 12 minutes.
• You will be wearing an upper body harness attached to the ceiling through a rope, which will be used to partially support your body weight in case you fall off the treadmill. This will reduce any injury risk associated with reaching maximal exertion at high running velocities.
• You will be allowed to complete a self-paced cool down following the test.

Visit 2: Meter Maximal Sprint Speed Test:

You will come to the University of New Mexico Athletics Track for a maximal sprint speed assessment. This visit will take place within 7 days of Visit 1. The procedure for this assessment is described below.

• You will complete a self-paced warm-up on the running track with jogging, light dynamic stretching and short sprints.
• For MSS assessment, you will perform one practice 45m sprint effort, followed by three maximal 45m sprinting efforts on the track. A timing system will be used to measure your speed over each 15m section of the 45m sprint. You will be allowed to take a rolling start of ~20m to 30m going into each sprint.
• Each all-out sprinting effort will be separated by a 5- to 10-minute recovery time.
• You will be allowed to complete a self-paced cool-down on the track.

Competition Performance Data:

In order to investigate the relationship between the ASR (MSS – MAS) and running performance, we will collect data regarding your season’s best racing performances over the 2020 Track and Field season. For the data to be included in this study, you will be required to finish at least one race over at least one of the following distances: 400m, 800m, 1500m/mile, 3000m, 5000m. By signing this consent form, you agree to research team members obtaining your season’s best racing times from result databases that are publicly available online. We may require you to confirm your season’s best performances in person or via email.

The research team would like to make clear that we do not intend for participation in this study to interfere with the athlete’s racing season. With this in mind, we encourage participants to follow their standard racing schedules and compete in their specialist race distances/ events they would normally compete in.

Risks:
**VO\textsubscript{2}max Risks**

There are risks associated with the maximal incremental exercise test including the following: muscle soreness, fatigue, nausea, or dizziness during or after completion of exercise. The incidence of risk of fatal and nonfatal events during maximal exercise testing are very low, approximately <0.8 per 10,000 tests or 1 per 10,000 hours of testing. We will minimize these risks by checking your medical history questionnaire for any medical conditions or history that could increase your risk, and by using trained personnel to conduct your testing. The occurrence of injury will result in immediate termination of the exercise test. The exercise laboratory is equipped with emergency medical equipment and have emergency procedures in place. You will be wearing an upper body harness to partially support your body weight in case you fall off the treadmill during the test. All researchers assisting in the trial have worked extensively with individuals performing high intensity exercise.

**Maximal Sprint Speed Test Risks**

There is risk of skeletal muscle damage from performing maximal sprint exercise. You will conduct a warm-up before the test to minimize the risk of injury.

**Performance Data Risks**

Subject information will be collected and displayed in the written report as both average and anonymous individual data, for example in graphic displays. We address the measures that have been put in place to keep your information confidential below.

In the very unlikely case of an emergency, standard procedures will be followed: these include calling 911 and monitoring the participant. All investigators are certified in CPR and AED use. One of the Exercise Physiology Laboratory’s on-call physicians, Christopher Bossart, MD or Jacob Christensen, MD, would also be notified immediately. The average time it takes for ambulance services to reach the Laboratory is approximately 5 – 8 minutes, and for a physician from the Student Health Center, less than 5 minutes.

**Benefits:**

There will be no direct benefit to the participant for taking part in this study. Participants will be given the results and interpretation of the MAS and MSS assessment at the completion of their participation. Participants will have the option to share this information with their coach, which could benefit both the athlete and coach in understanding the athlete’s current physiological profile, and have implications for adapting training programs accordingly. You will also receive results from the body composition assessment, via the skinfold method.

**Compensation:**

There will be no compensation for participation in this study.

**Confidentiality of your information:**

To protect your information, you will receive a subject number with no link to your name on any study material. Only the research team will know what you do or say in this study. All
information obtained during your participation in this study will be viewed only by the research team and kept in a locked cabinet and on a password protected computer in Fabiano Amorim’s office. The University of New Mexico Institutional Review Board (IRB) that oversees human subject research may be permitted to access your records. Your name will not be used in any published reports about this study. All electronic data generated during the course of the study will be managed in compliance with the general guidelines for the Use of Confidential Data.

All identifiable information (e.g. your name) will be removed from the information or samples collected in this project. After we remove all identifiers, the information or samples may be used for future research or shared with other researchers without your additional informed consent.

Right to withdraw from the study:

Your participation in this research is completely voluntary. You have the right to choose not to participate or to stop participating at any time without penalty. If you withdraw once the project has begun, you can request that your data not be used for research by writing or emailing a short note to Fabiano Amorim.

If you have any questions, concerns, or complaints about the research, please contact the principal investigator: Fabiano Amorim, Ph.D., Department of Health, Exercise & Sport Sciences, 1 University of New Mexico, Albuquerque, NM, 87131. They may be reached Monday-Friday 8:00 a.m. – 5:00 p.m. at (505) 277-2664, or anytime via email at amorim@unm.edu.

If you have questions regarding your rights as a research participant, or about what you should do in case of any research-related harm to you, or if you want to obtain information or offer input, please contact the IRB. The IRB is a group of people from UNM and the community who provide independent oversight of safety and ethical issues related to research involving people:

UNM Office of the IRB, (505) 277-2644, irbmaincampus@unm.edu. Website: http://irb.unm.edu/

CONSENT

You are making a decision whether to participate in this study. Your signature below indicates that you have read this form (or the form was read to you) and that all questions have been answered to your satisfaction. By signing this consent form, you are not waiving any of your legal rights as a research participant. A copy of this consent form will be provided to you.

I agree to participate in this study.

_________________________________   ___________________________   ______
Name of Adult Participant    Signature of Adult Participant   Date

Researcher Signature (to be completed at time of informed consent)
I have explained the research to the participant and answered all of his/her questions. I believe that he/she understands the information described in this consent form and freely consents to participate.

<table>
<thead>
<tr>
<th>Name of Research Team Member</th>
<th>Signature of Research Team Member</th>
<th>Date</th>
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APPENDIX B

HEALTH HISTORY QUESTIONNAIRE

Date___/___/___

Subject #_______

Age____ Ethnicity_______    Phone (W)__________________email___________________

MEDICAL HISTORY

Self-reported: Height______    Weight______

Physical injuries:__________________________________________________________

Limitations:______________________________________________________________

Have you ever had any of the following cardiovascular problems? Please check all that apply.

Heart attack/Myocardial Infarction____ Heart surgery____ Valve problems____
Chest pain or pressure _______ Swollen ankles____ Dizziness____
Arrhythmias/Palpitations _______ Heart murmur_____ Arrhythmias____
Shortness of breath ________ Congestive heart failure____

Have you ever had any of the following? Please check all that apply.

Rheumatic fever_____ High blood pressure_____ Thyroid problems____
Kidney/liver disease_______ Obesity_____ High cholesterol____
Diabetes (specify type)______ Asthma____ Seizures____
Emphysema_______ Stroke____ Cold Injury____

Is your mother living?  Y   N  Age at death______ Cause___________________
Is your father living?   Y   N  Age at death______ Cause___________________

Have you ever been diagnosed with a gastrointestinal disease or disorder?  
Y        N

Have you ever been diagnosed with a food allergy          Y     N

Have you ever experienced a heat related illness?   Y     N

Do you currently have any condition not listed that may influence test results?  
Y  N

Details____________________________________________________________________
_________________________________________________________________________
Indicate level of your overall health. Excellent ____  Good ____  Fair ____  Poor_____
Are you taking any medications, vitamins or dietary supplements now, especially including glutamine, any chemotherapy drugs, anti-depressants or gabapentin (Neurontin)?
Y        N
If yes, what are they?________________________________________________________________
Are you taking any non-steroidal anti-inflammatory medications (i.e. aspirin, ibuprofen, Naproxen)
Y        N
Do you have allergies to any medications? If yes, what are they?
___________________________________________________________
Have you been seen by a health care provider in the past year?    Y        N
If yes, elaborate
____________________________________________________________________
Women only: are you pregnant or considering becoming pregnant in the next two months?
Y   N

LIFESTYLE FACTORS
Do you now or have you ever used tobacco?     Y    N     If yes:  type ________________
How long?______    Quantity_____/day    Years since quitting___________
How often do you drink the following?
Caffeinated coffee, tea, or soda _____oz/day    Hard liquor _____oz/wk    Wine
________oz/week
Beer _______oz/wk
Indicate your current level of emotional stress. High____    Moderate ____    Low____

PHYSICAL ACTIVITY/EXERCISE
Physical Activity
How many days per week do you exercise (average)? _________ days
How many minutes per exercise session (average)? _________ minutes
Do you train in any activity (eg. jogging, cycling, swimming, weight-lifting)?    Y        N
What is your preferred type of exercise? ____________________________________________
How many minutes of high intensity exercise or vigorous exercise do you perform each week?_________mins
APPENDIX C

DATA COLLECTION FORM

DATE:
SUBJECT #:
HEIGHT (cm): WEIGHT (kg):
RESTING BLOOD PRESSURE: /

BODY COMPOSITION:

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**MAXIMAL AEROBIC SPEED ASSESSMENT:**

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SUBJECT #:  
TEST START TIME:  

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END TIME: 
TOTAL TEST DURATION: 
END RPE: 
VO$_2$ MAX: 
vVO$_2$ MAX: 

Reason for stopping:
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### MAXIMAL SPRINT SPEED TEST

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**SUBJECT #:**

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**FASTEST 15 METER SEGMENT (sec):**

**MSS:**

**Notes:**

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