From theory to practice:

Running kinematics of triathletes

By

AMY CLARE SCARFE

A thesis submitted to The University of Birmingham for the degree of

DOCTOR OF PHILOSOPHY

School of Sport and Exercise Sciences

College of Life and Environmental Sciences

The University of Birmingham

June 2011

Abstract

Triathlon comprises of three disciplines: swimming, cycling and running. Of these, running performance has been found to be most strongly related to race success. Studies investigating the effect of long term multidisciplinary training on running technique are limited. This thesis set out to further explore these chronic adaptations and apply this theoretical understanding to investigate training modification in triathlon.

Results of the first two experiments showed that long term kinematic adaptations to running, present in both male and female triathletes. This is most likely due to the volume of cycling undertaken and the subsequent effect it has on the hip musculature. Consequently, a hip flexibility programme was designed and implemented. However, despite improvements in static flexibility, this programme did not affect running technique. In a subsequent study, flexibility training combined with running technique drills also failed to bring about any modifications in running kinematics. Findings of a longitudinal case study demonstrated that, in addition to chronic and acute running technique adaptations, intermediate changes linked to varying training demands also exist showing the level of variability of the running technique.

It is concluded that adaptations to cycling are the cause of differences in running technique between triathletes and runners and that these modifications are difficult to reverse. However, the additional intermediate variations observed demonstrate technique can be changed as a result of training requirements.

Acknowledgments

First and foremost, I would like to thank my supervisors, Francois-Xavier Li and Trevor Gardner for providing me with the opportunity to undertake this PhD. I am grateful for all of the help, support and guidance you have provided me throughout.

I would also like to extend my thanks to Nicola Heneghan and Steve Lumley for sharing with me, their respective knowledge of physiotherapy and triathlon. I also thank all of my undergraduate students for their assistance during data collection for each study. To each and every participant who took part in my studies, thank you. Without your efforts and commitment, this thesis would not have been possible. A special mention must also be given to the elite participant who took part in Chapter 7, in spite of your training and travel commitments you still made time to (and never once complained about) the numerous data collection sessions. It has been a privilege to work alongside such a talented and determined person.

Thank you to all of my friends within the SportEx community; the endless cups of tea, the great laughs and of course the Friday nights in Staff House have certainly helped me get through the rollercoaster journey of the past three years.

And now to my family. Ma and Pops, thank you for your eternal love, support and encouragement. It goes without saying that, without you, I would not have finished my first year in undergrad, let alone have got to the stage I am at now. My sisters, Katie, Laura and Louise, thank you for always being there for me. Whenever I need good moan, laugh or cry, I know that you are all, always on hand. My brother-in-law, John, it was with your entrance in to the family, that the notion of a PhD entered my brain. Thank you for the initial inspiration, and for your support and proof reading skills along the way. Finally, my niece, Imogen Jane. Thank you for taking my mind off work when I needed it, your unquestioning love and for making me the proudest auntie in the world. Thank you all.

List of Figures

Chapter 1: INTRODUCTION

Chapter 2: GENERAL METHODS

Chapter 3: RUNNING IN TRIATHLON: THE EFFECT OF PREVIOUS RUNNING EXPERIENCE ON STRIDE PARAMETERS AND KINEMATICS

Chapter 4: FEMALE TRIATHLETE STRIDE PARAMETERS AND RUNNING KINEMATICS IN COMPARISON TO RUNNERS

Chapter 5: HIP FLEXIBILITY IN TRIATHLON

Chapter 6: THE EFFECT OF RUNNING TECHNIQUE DRILLS AND HIP FLEXIBILTY TRAINING ON TRIATHLETE RUNNING KINEMATICS

Chapter 7: A LONGITUDINAL CASE STUDY OF AN ELITE FEMALE TRIATHLETE

List of Tables

Appendix D: SUPPLEMENTARY DATA

Abbreviations

ASIS - Anterior Superior Iliac Spine

COM - Centre of Mass

Hz - Hertz

IC - Initial Contact

IP - Iliopsoas

MSt - Mid-Stance

MSw - Mid-Swing

RF - Rectoris Femoris

ROM - Range of Motion

SF - Stride Frequency

SL - Stride Length

SL:LL - Stride Length relative to Leg Length

TO - Toe Off

Chapter 1: GENERAL INTRODUCTION

1.1 **Triathlon**

Although a unitary event, the endurance sport of triathlon is comprised of 3 separate disciplines: swimming, cycling and running and is performed over a series of distances (Table 1.1). Optimal performances in each discipline, as well as efficient transition between the three elements (swim-to-cycle and cycle-to-run) are key to successful overall triathlon performance (Bentley et al., 2002).

Table 1.1: Triathlon race distances (km)

Distance	Swim	Bike	Run
Super Sprint	0.2	10	2.5
Sprint	0.75	20	5
Olympic	1.5	40	10
Long-Distance (O2)	3.0	80	20
Half Ironman	1.9	90	21.1
Long-Distance (O3)	4.0	120	30
Ironman	3.8	180	42.2

In order to achieve the best possible performance, triathletes rely on their ability to perform the three vastly different movement patterns of each discipline as efficiently as possible, with minimal interference from the other constituent parts. The multifaceted nature of triathlon, together with volume of training undertaken by triathletes, may, however, predispose them to neuromuscular adaptations that optimise overall triathlon performance whilst having have adverse effects on the individual disciplines (Chapman et al., 2004).

Of the three disciplines that combine to form triathlon, running has been highlighted as the greatest predictor to overall race outcome (Millet and Bentley, 2004; Vleck et al., 2008). Triathletes therefore rely heavily on their ability to run efficiently without displaying any adverse adaptations to either the preceding cycling leg or as a result of their multidisciplinary training regime (Bonacci et al., 2010a; Saunders et al., 2004).

1.2 Running Gait Cycle

In order to explore the running kinematics associated with triathlon, a brief introduction to the running gait cycle is necessary. This, along with typical spatio-temporal parameters, joint kinematics and previously published optimisation suggestions are presented below.

The gait cycle is defined as the period from initial contact of one foot until ipsilateral initial contact. The gait cycle can be divided into 2 phases: the stance phase, when the foot is in contact with the ground, and the swing phase, when the foot is not in contact with the ground. The running gait cycle is distinguished from the walking gait cycle by the characteristic periods of double float that occur at the beginning and end of the swing phase during which neither foot is in contact with the ground. The stance phase can be further subdivided into absorption and propulsive phases (Figure 1.1).

During the running gait cycle, approximately 40% of the cycle is spent in stance and 60% in the swing phase (including the two periods of double float that each account to 15% of the cycle). As running velocity increases, time spent in stance decreases and there is a corresponding increase in swing time (Dicharry, 2010).
Although joint movements associated with running are frequently discussed as individual entities, movement of body segments are coordinated actions in a closed

kinetic chain during the stance phase and open kinetic chain during the swing phase (Dicharry, 2010). Given the forward direction of travel during running, the principal joint movements occur in the sagittal plane.

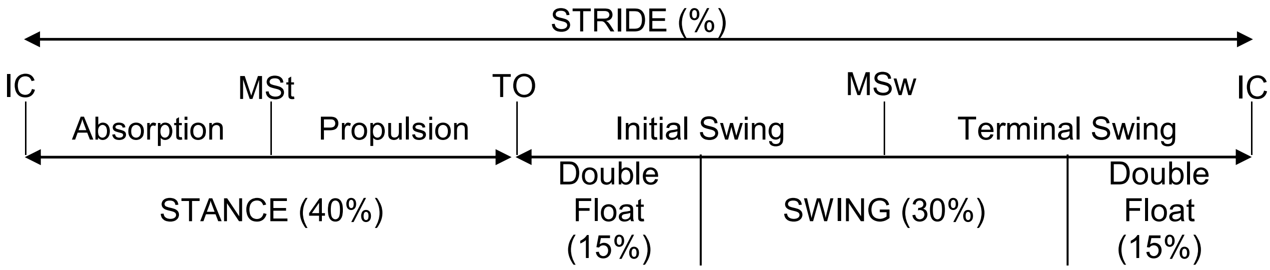

Figure 1.1: The phases and events of the running gait cycle (IC - initial contact; MSt - mid-stance; TO - toe off; MSw - mid-swing). Adapted from Thordarson (1997).

Initial contact is accompanied by rapid flexion of the hip, knee and ankle in order to absorb some of the force of impact (Thordarson, 1997). During the absorption phase of stance (from initial contact to mid-stance), the knee and ankle continue to flex enabling further shock attenuation. Mid-stance is defined as the point at which the transition from absorption to propulsion occurs and is identified by the cessation of the shock absorbing flexion and the commencement of joint extension (Thordarson 1997). It is at this point that centre of mass (COM) of the body reaches its vertical minimum (Farley and Ferris, 1998).

Peak hip, knee and ankle extension occur at toe-off and enable translation of propulsive forces in a horizontal direction (Chang and Kram, 1999; Chang et al., 2000). During swing phase, both the hip and knee flex to clear the limb in swing (Dicharry, 2010). In the latter part of the swing phase, hip extension begins to occur in order to allow position the foot under the body at initial contact. Without this extension, foot placement would be ahead of the centre of mass and cause ground reactions forces to occur in a posterior direction, resulting in deceleration (Dicharry, 2010).

1.3 **Optimal running kinematics**

Optimum endurance performance is reliant upon the translation of cardiorespiratory factors into well controlled, efficient movement and muscle recruitment patterns (Chapman et al., 2009). Accordingly, the biomechanics of endurance running has received much attention within the scientific literature and a number of differences have been identified between runners of varying abilities.

In comparison to slower runners, fast runners display longer strides (Dillman, 1974; Saito et al., 1974; Weyand et al., 2000) and a variety of kinematic variables have been identified in association with this including increased hip flexion during swing (Williams and Cavanagh, 1987; Mann and Hagy, 1980), increased knee flexion during mid-swing (Dillman, 1974) and increased hip extension at toe-off (Dillman, 1974; Novacheck, 1998).

Anterior pelvic tilt and hip extension have been shown to be highly coordinated actions in both running and walking, with increased pelvic tilt accompanied by decreased hip extension (Schache et al., 2001; Franz et al., 2009) (Figure 1.2).

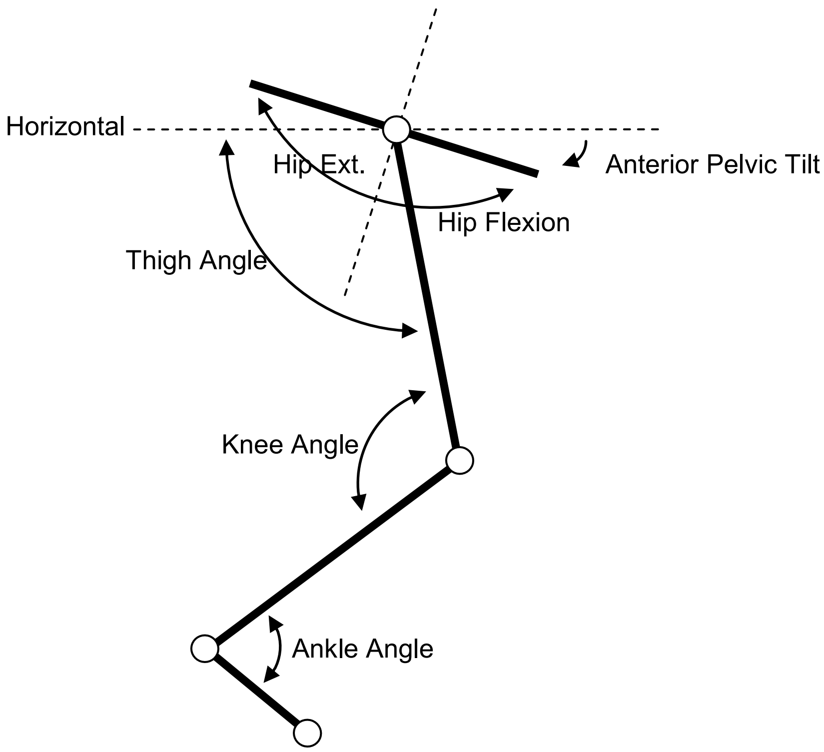

Figure 1.2: Joint angle definitions. Hip extension and anterior pelvic tilt are coordinated actions (Schache et al., 2001). Thigh angle is calculated relative to the horizontal to differentiate between the movements of the pelvis and the thigh segment.

This association, together with the importance of hip extension during toe-off, indicate that pelvic tilt may also be an important factor in determining stride length. Furthermore, Novacheck (1998) suggested that increased pelvic tilt in association with increased velocity enables greater thigh extension and subsequently a more efficient, horizontal application of propulsive forces (Figure 1.3).

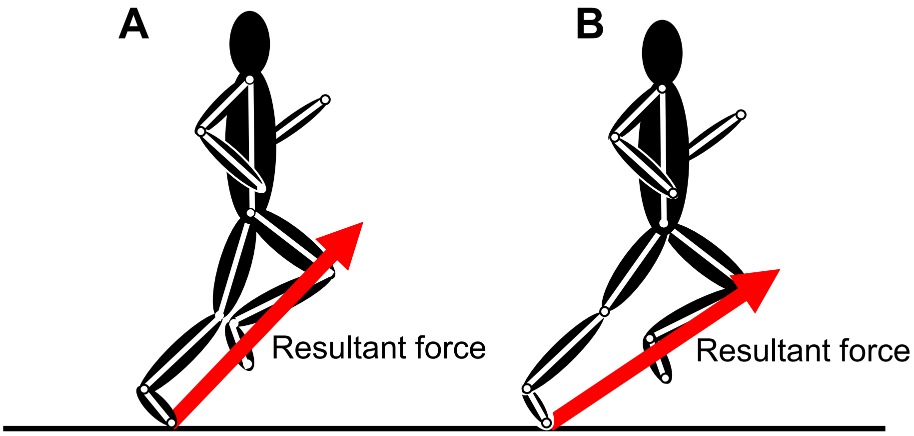

Figure 1.3: Thigh extension is important for directing propulsive forces. Increased extension at toe off may result in a more horizontal propulsive force (B).

Given that approximately a third of the total metabolic cost of running is associated with the generation of such propulsive forces, altering running gait to allow greater horizontal force generation at no extra energetic cost could enhance performance (Chang and Kram, 1999; Chang et al., 2000).

1.4 **The effect of cycling on running kinematics**

Triathletes of varying experience and ability report, anecdotally, that prior cycling causes a lack of coordination during the subsequent run (Bonacci et al., 2010a; Hausswirth and Brisswalter, 2008; Heiden and Burnett, 2003). Empirical evidence suggests that short term running adaptations post cycling include reduced stride length and subsequent increased stride rate, increased forward trunk lean, altered knee angle in both the swing and stance phase of the running cycle and increased energy, mechanical, potential and kinetic costs whilst running post cycling (Hausswirth et al., 1997; Gottschall and Palmer, 2000; Millet and Vleck, 2000 and Millet et al., 2001). Such adaptations to cycling have been linked to compromised running performance within triathlon (Tew, 2005) and reduced running economy

(Bonacci et al., 2010a). Altered muscle recruitment patterns when running-off-the-bike have also been reported (Chapman et al., 2009). Given that this was linked to exercise-related leg pain this may not only be detrimental to running performance but may identify an injury risk within triathletes (Bonacci et al., 2010b).

Even when running ‘fresh’ (i.e. not off the bike) triathletes display a different running gait to pure runners, exhibiting shorter relative strides and decreased hip ROM, thigh extension, hip flexion and anterior pelvic tilt (Connick, 2009). These authors’ identified the large volumes of cycling training undertaken by triathletes (Gulbin and Gaffney, 1999; O’Toole, 1989) and the flexed position the hips and pelvis are maintained in throughout as the potential cause (Connick, 2009). In endurance events, this requires the hips and knees to be maintained in a flexed position for long durations, both in races and training (Callaghan, 2005). The extremely flexed position of cycling means that the mono-articular muscles of the vastii group operate over a much longer range than in running, where knee extension minimises the muscular length required. This causes optimal power generation in this muscle group to occur at much longer lengths in cyclists than runners (Salvberg and Meijer, 2003). Similarly maximal biceps femoris strength has been found at shorter lengths in cyclists than in runners (Herzog et al., 1991), and as such, large volumes of cycling may not be conducive to optimal running performance.

Whilst cycling appears to have a detrimental effect on running performance when considered in unison, this may not be the case when considered in the combined sport of triathlon. It may be the case that differences between triathlete and runner running technique are due to muscular adaptations that allow optimal performance throughout the entire multidiscipline event rather than each individual discipline (Chapman et al., 2004).

The manifestation of long-term running adaptations to cycling as seen in triathletes are examined in Chapters 3, 4 and 7 of this thesis.

1.5 Gender differences in running kinematics

Although gender differences in walking kinematics have been widely reported (Li et al., 2001; Kerrigan et al., 1998), running kinematic differences have received much less attention (Ferber et al., 2003). Given that both differences in structure between genders (Livingston, 1998; Simoneau et al., 1998) and differences in running mechanics has been postulated to be the cause for differing injury aetiologies between males and females (Ferber et al., 2003), it seems surprising that only a small number of published articles have sought to address this issue.

In the non-sagittal planes, females exhibit greater peak hip internal rotation and adduction (Ferber et al., 2003; Chumanov et al., 2008) and greater peak knee abduction (Ferber et al., 2003; Malinzik et al., 2001) than males. Additionally, females demonstrate greater peak-to-peak joint rotations in all planes in the lumbo-pelvic-hip complex apart from in pelvic tilt; in this variable females exhibit an offset of approximately 4° greater than their male counterparts (Schache et al., 2003).

Gender differences in anthropometric measures and the difference in spatio-temporal parameters of running gait of males and females have been speculated to be the underlying cause of such differences (Ferber et al., 2003; Schache et al., 2003). However, when these factors were taken in to account, the only anthropometric variable found to be a significant predictor of joint angular rotations of the lumbo-pelvic-hip region during running was standing pelvic tilt (Schache et al., 2003). Moreover, the same authors report that even though several spatio-temporal parameters were also found to be predictors of specific angular rotations, the most common variable related to the differing magnitudes of joint rotations was gender. Studies addressing the long term effects of cycling training upon running kinematics have, to the author's knowledge, only addressed this issue in males (Connick, 2009). Given the apparent differences between male and female running technique it is plausible that such adaptations may be different between genders.

The gender specific issues surrounding long-term adaptations to triathlon will be addressed in Chapters 4 and 7 of this thesis.

1.6 **Running technique modification**

Running mechanics appear to have a relationship with performance related parameters, be it running economy, velocity or ability. Subsequently, many authors have investigated the effect of manipulating specific kinematic variables in isolation to examine the effect on running performance. Additionally, longer-term, wider targeted, training intervention programmes to facilitate modified running performance have been suggested and implemented.

Stride length and subsequently stride rate are both factors suggested to be related to faster running and improved running economy. A number of studies, which have sought to investigate the effect manipulating these parameters has on running economy, found that optimal step lengths and frequencies exist (Cavanagh and Williams, 1982; Kaneko et al., 1987; Heiderscheit et al, 2011). Cavanagh and Williams (1982) suggest that experienced runners pick a stride rate that is close to optimal. Moreover, Kaneko et al (1987) first established, based on oxygen consumption, vertical ground reaction force and mechanical work estimates, the optimum stride rate of their participants. Manipulation of participants' gait demonstrated that when displaying optimal stride rate, vertical force application (indicative of vertical oscillation), external work and submaximal oxygen consumption were all reduced. However, stride rates above this frequency, led to increased external work and oxygen consumption. In a recent publication, Heiderscheit et al., (2011) found that even small stride rate manipulations of 10% or less, result in running kinematic changes associated with improved economy. A major limiting factor of the aforementioned studies is that the findings they present are based on short term modifications of individual gait parameters.

Global alteration of running technique has been shown to affect running economy (Petray and Krahenbuhl, 1985; Dallam et al., 2005; Vseh et al., 2008). Vseh et al., (2008) found that large scale alterations, such as running with hands behind the back, hands on the head and exaggerated vertical oscillation, over a short time frame (6 minutes), led to decrements in running economy when compared to normal running in trained female runners. More subtle short-term modifications, such as instruction to run with a mid-foot strike or in Pose style, have also been found to bring about changes in running kinematics (Arendse et al., 2003). Although economy measures were not reported in this study, changes in the kinematic measures of stride length, vertical oscillation and ankle contact angle may be

associated with changes in this measure. Longer term studies, such as that by Dallam et al., (2005) demonstrated that following 12 weeks of training and tuition in the Pose method of running brought about significant decreases in stride length and vertical oscillation and a subsequent increase in submaximal oxygen cost.
The effect of specific training modalities on running technique and economy has also been examined. For example, flexibility training has been found to have mixed effects on running economy with some authors reporting a negative effect (Gleim et al., 1990; Craib et al., 1996) and others reporting a positive effect (Godges et al., 1989; Sandell et al., 2008). Specifically, Craib et al., (1996) found that 47% of running economy variance in their study was explained by external hip rotation and dorsi-flexion flexibility, with participants who demonstrated the least flexibility exhibiting the greatest running economy. Conversely, Godges et al., (1989) reported that, in a group of moderately trained runners, oxygen consumption decreased by approximately 2ml/kg/min over a range of velocities after an acute bout of static stretching that increased both hip flexion and hip extension. In a group of middle distance runners, Sandell et al., (2008) found that increased hip extension flexibility, brought about through a 3 week chiropractic treatment programme, resulted in a greater increase in post-intervention velocity in the treatment group than in the control group.

It is clear from all of these aforementioned studies that manipulation of running gait, be it through short term modifications, running technique training programmes or training modalities, can lead to modified running technique and subsequent changes in running performance measures.

Issues surrounding modification of running technique are addressed in Chapters 5, 6 and 7 of this thesis.

1.7 Thesis Aims

The primary aim of this thesis is to demonstrate the progression from theoretical understanding to applied practice in a sports setting. A growing body of evidence suggests that the running technique of triathletes is liable to chronic adaptations in response to the multidisciplinary nature of triathlon. However current research is limited to a description of the differences between runners and triathletes and the cause of these modifications, the manifestation of the adaptations in different populations and methods to minimise or reverse such adaptations are all yet to be investigated.

This thesis is therefore presented as two parts: the first part aims to explore the running technique of triathletes further and develop an improved understanding of the long term adaptations triathletes' exhibit in their running technique, seemingly in response to the multifaceted nature of triathlon. In the second part, this understanding will be used firstly to design and implement intervention programmes aimed at modifying the running technique used by triathletes. Secondly, the theoretical basis developed in the initial part of this thesis will then be used in the long term analysis of an elite triathlete.

Chapter 2: GENERAL METHODS

2.1 Introduction

Each of the following experimental chapters contain specific details of study design and procedures relevant to the chapter. However, the protocols by which kinematic data and hip flexibility data were collected were identical throughout the thesis and details of these methods follow.

2.2 Participants

Specific recruitment criteria of participants for each study of this thesis is presented within the empirical chapters, however some general requirements remained constant throughout all of the empirical chapters.

All participants were endurance athletes, with at least 2 years experience of competing and training either within a club or with a coach in their chosen sport. Details of participants sporting history and training regimes were gathered via conversation and a sport specific questionnaire (Appendix A) that all participants filled out prior to testing. All participants were aged over 18 and less than 45 years. At the time of testing, all participants were healthy and injury free, this was assessed by both verbal communication and a general health questionnaire (Appendix A) that was completed by everyone who took part in the studies. Prior to data collection, all participants received an information form about the study (Appendix B) and subsequently all provided written informed consent (Appendix C).

Due to the similar nature of the studies that constitute this thesis, and the similar recruitment criteria of participants, there was some overlap of participants. Specifically, 3 of the participants from the pure triathlete group in Chapter 2 took part in the flexibility study of Chapter 4 and an additional participant from Chapter 2 and 2 of the female participants from Chapter 3 participated in the flexibility and drills study (Chapter 5). No participant took part in both of the flexibility studies.

2.3 **Motion Capture**

All data collection sessions commenced with a 5 minute warm up run at 10km/h on an h/p Cosmos treadmill. Kinematic data were captured using a 13 camera Vicon MX (Oxford Metrics, UK) system at 250Hz. Reflective markers were placed by a single tester, bilaterally, on 20 anatomical landmarks; the anterior superior iliac spine (ASIS), posterior iliac spine (PSIS), greater trochanter, medial and lateral femoral epicondyles, medial and lateral malleoli, the posterior aspect of the calcaneous and the heads of the 1st and 5th metatarsals. Additional tracking markers, to aid data reconstruction, were placed bilaterally on the frontal and lateral aspect of the thigh, tibial tuberosity, posterior aspect of lower leg and 2nd metatarsal head (Table 2.1).

Following marker attachment, participants were instructed to stand within the capture volume, in the anatomical reference position, in order for a static trial to be collected. Following this, participants carried out 3 x 2-minute bouts of running on the same treadmill used for the warm up, at 3 different velocities (details of the specific velocities used can be found in each experimental chapter). These were performed in a random order, each separated by a passive recovery period to allow heart rate to return to post-warm up levels. Motion data were captured using Vicon Workstation for 35 seconds in the final minute of each running bout.

Table 2.1: Marker placements (tracking markers in italics) and variable definitions.

Segment	Anatomical markers ***Tracking Markers***	Variable definitions
Pelvis	Anterior superior iliac spine (ASIS) Posterior superior iliac spine (PSIS)	**Pelvic Tilt:** Angle between the vector from the mid point of ASIS markers to mid point PSIS markers and horizontal
Thigh	Greater trochanter Medial and lateral femoral epicondyle *Frontal aspect of thigh* *Lateral aspect of thigh*	**Thigh angle:** Angle between the thigh and horizontal **Hip flexion/extension:** Angle between the pelvis and thigh segments
Shank	Medial and lateral femoral epicondyle Medial and lateral malleoli *Tibial tuberosity* *Posterior aspect of lower leg, superior to heel counter*	**Knee flexion/extension:** Angle between the shank and thigh segments
Foot	Head of the 1st and 5th metatarsals Posterior aspect of the calcaneous *Head of the 2nd metatarsal*	**Ankle flexion/extension:** Angle between the shank and foot segments

Whilst the use of a treadmill may decrease some of the ecological validity, it enables well-standardised, easily repeatable data collection. Moreover, only minimal differences in rotations of the lumbo-pelvic-hip have been found between treadmill and overground running (Schache et al., 2001). However, previous literature is inconclusive as to the ideal time to allow for accommodation to the treadmill; Fellin and Davis (2009) suggest that 3 minutes is sufficient, whilst Lavcanska et al., (2005) report that 6 minutes is needed to minimise changes in sagittal plane kinematics and

Hardin et al., (2004) found that hip extension is significantly greater after 15 minutes of running than after 5 minutes. The need for such familiarisation is, however, reduced in participants are habitual treadmill runners (Wall and Charteris, 1981, cited by Lavcanska et al., 2005), this study demonstrated that participants who carried out weekly treadmill running took only 1 minute to demonstrate a stable running gait. Therefore, where possible, all participants were experienced treadmill runners (apart from the cyclists tested in Chapter 3) and running bouts of 2 minutes were chosen to allow accommodation to treadmill running, whilst minimising any potential fatigue effecting running kinematics.

The global coordinate system followed the right-hand convention, with the positive z-axis parallel to the forward running direction of the treadmill, the y-axis perpendicular to the z-axis (positive to the left) and the positive x-axis located upwards, perpendicular to the z and y-axes (Schache et al, 2001).

Participants wore their normal running shoes for all tests and, in studies where kinematic data was collected on multiple occasions (Chapters 5, 6 and 7), requested to wear the same footwear for each data collection session.

2.4 **Kinematic Processing**

Raw data were collected and subsequently tracked within Vicon Workstation and exported to and analysed using Scilab v4. Using custom scripts, data were filtered using a finite response filter (cut off frequency 12 Hz) and normalised to the gait cycle. Kinematic data of 10 consecutive right foot contacts were analysed.

Using the method previously reported by O'Connor et al., (2007), determination of foot contact was based on positional data of the heel and 5th metatarsal markers. Initially a Preliminary Foot Contact (PFC) was calculated based on total vertical motion thresholds of the heel marker (10%) and 5th metatarsal marker (35%). PFC was the point at which both of the markers were found to be under their allocated threshold. A 16 frame window was subsequently established around PFC and foot contact was deemed to be the peak acceleration during this period. Stride length was defined as the mean distance covered between right foot contacts.

The pelvis segment was determined by the bilateral ASIS and PSIS markers and in order to calculate pelvic tilt, a vector from the mid point of the anterior markers to the mid point of the posterior markers was used. Pelvic tilt was defined as the angle between this vector and the horizontal Schache et al., (2002).

The thigh segment was defined as the vector between the greater trochanter and knee markers and the shank segment the vector between the lateral epicondyle marker and the lateral malleolus. Thigh angle was the angle calculated between the thigh segment and the horizontal, hip angle the angle between the pelvis and thigh segments and knee angle the angle between the shank and thigh (Figure 2.1).

Data processing methods and joint angle definitions have been documented previously (Connick, 2009).

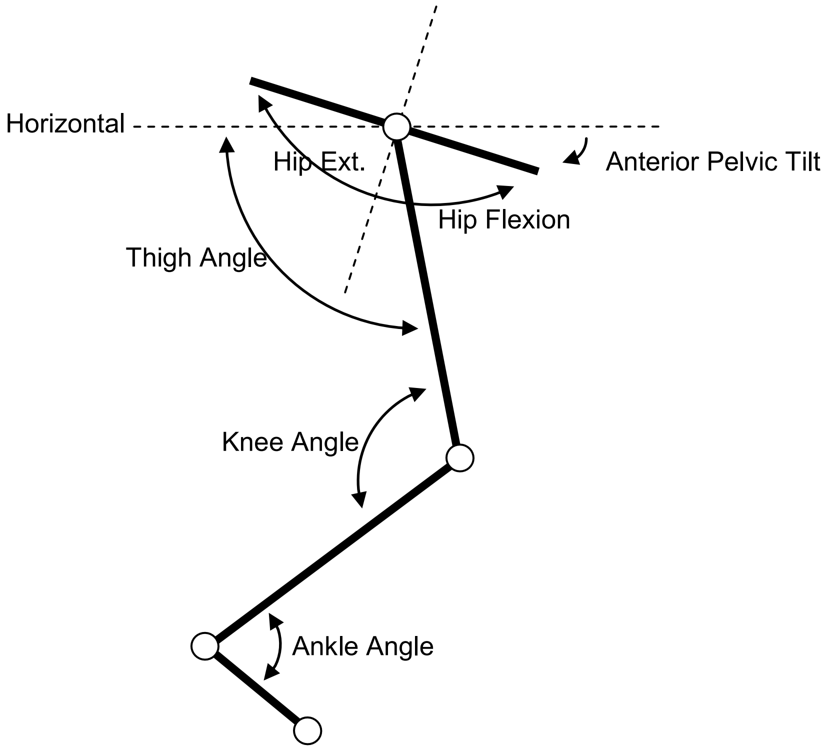

Figure 2.1: Joint angle definitions. Hip extension and anterior pelvic tilt are coordinated actions (Schache et al, 2002). Thigh angle is calculated relative to the horizontal to differentiate between the movements of the pelvis and the thigh segment.

2.5 **Test-retest reliability of kinematic data**

The interpretation of kinematic data is reliant upon accurate and repeatable marker placement, particularly in test-retest study designs (Pohl et al., 2010). Throughout this thesis, certain methodological steps have been taken in order to minimise errors caused by marker placement, these included:

- Analysis of only sagittal plane data as data from other planes have been shown to be more prone to errors (Laroche et al., 2011)
- A single, experienced experimenter was responsible for all marker placements. Between experimenter errors have been found to be greater than within experimenter measures (Pohl et al., 2010).

- All running analysis was carried out on a treadmill thus standardising velocity, minimising side to side movement and irradiating the effect of targeting during trials (Pohl et al., 2010).
- Analysis of data from multiple strides has been show to increase reliability of kinematic data (Pohl et al., 2010; Diss, 2001).

Furthermore, in order to aid interpretation of the data throughout this thesis, kinematic data was collected from 3 participants (using the aforementioned collection and analysis methods) on 3 separate occasions. Reliability was assessed using two-way intra-class coefficient correlations (ICC) and their 95% confidence intervals (CI), an ICC greater than 0.7 was considered good and greater than 0.9 considered excellent. This method of assessing reliability of gait kinematics has previously been documented by Laroche et al., (2011).

Table 2.2: Test re-test reliability of running kinematics.

	Difference (RMS ±SD)	**ICC**	**95% CI**
Stride Length (m)	0.10 ± 0.05	0.96	0.696→0.999
Peak hip extension (deg)	2.80 ±1.47	0.85	0.212→0.996
Peak anterior pelvic tilt (deg)	3.49 ± 2.87	0.63	0.001→0.933
Peak thigh angle (deg)	3.08 ±1.79	0.80	0.061→0.994

Results indicate that, of the key variables examined in this thesis, stride length, peak hip extension and peak thigh angle are highly reliable measures, with ICCs ranging from 0.80-0.96. In accordance to previous studies, pelvic tilt is somewhat less reliable with an ICC of 0.63. This has previously been associated with the difficulty in locating the PSIS marker placement (Pohl et al., 2010). This should be noted when interpreting subsequent findings of this thesis.

2.6 Static hip flexibility assessment

Static hip flexibility was measured in a number of the following experimental chapters (3, 5 and 6). This was assessed using the modified Thomas test (Schache et al., 2000) and a digital inclinometer (Acumar Model ACU001, Lafayette Instrument Company, USA) with measurement resolution of 1-degree. These clinical tests were carried out by the same experimenter to ensure correct technique and repeatability. Participants were instructed to sit on the end of a plinth and roll back on to the plinth. Once in this position they held both knees to the chest ensuring that the lumbar spine was flat on the plinth and the pelvis in a posterior rotation. The contra lateral hip was held in maximal flexion by another experimenter, while the tested limb was lowered towards the floor first with the knee bent (to assess rectus femoris flexibility - RF) and with the knee straight (to assess iliopsoas flexibility - IP). Participants were instructed to perform a maximal stretch in each position. The angle of hip extension was measured using the digital inclinometer and each measure was repeated 3 times and with the mean measure recorded for each limb, in each position.

2.7 Test-retest reliability of static hip flexibility measures

As with the kinematic data, test re-test reliability is important in the interpretation of the static flexibility measures. Therefore, flexibility data was also collected from 3 participants using the aforementioned methods.

Results demonstrate that both flexibility measures are highly repeatable, with ICCs of 0.78 and 0.84 for the RF and IP respectively (Table 2.2).

Table 2.3: Test re-test reliability of static flexibility measures.

	Difference (RMS ±SD)	ICC	95% CI
RF static flexibility (deg)	3.34 ± 1.84	0.78	0.021→0.993
IP static flexibility (deg)	1.91 ±0.48	0.84	0.160→0.988

Chapter 3: RUNNING IN TRIATHLON: THE EFFECT OF PREVIOUS RUNNING EXPERIENCE ON STRIDE PARAMETERS AND KINEMATICS

3.1 **Abstract**

Cycling has been proposed to be the underlying cause of the differences in running technique between triathletes and runners. In order to maximise aerodynamics, cycling is often carried out in an extremely flexed posture (Callaghan, 2005). This position requires the hips and knees to be maintained in a flexed position for long durations, which may subsequently cause a shortening of the hip flexor musculature.

In order to investigate the long-term adaptations to cycling, the running technique of 9 *pure* triathletes who had no running experience prior to taking up triathlon, 9 triathletes with a running background, 9 runners and 9 cyclists were explored. At each velocity investigated, runners exhibited the greatest stride length, hip ROM, thigh extension and anterior pelvic tilt, followed by triathletes with a running background, *pure* triathletes and cyclists. No differences were found between the groups of triathletes.

Furthermore, the static hip extension flexibility of 5 triathletes and 5 cyclists was assessed and found be less than in 5 pure runners. Flexibility measures in triathletes and cyclists were found to be related to running kinematics in these groups but not in runners.

It is concluded that large volumes of cycling is likely to result in adaptive shortening of the hip flexors and that this subsequently affects the running technique of triathletes and cyclists.

3.2 Introduction

The movement patterns associated with swimming, cycling and running are vastly different from one another and substantial training in any one of these disciplines may have a detrimental effect on the others. The sport of triathlon combines these three disciplines, and, given its endurance nature, competitors must undertake large volumes of training in each discipline in order to perform at their maximum capability.

The primary determinant of triathlon race success has been found to be running performance (Millet and Bentley, 2004; Vleck et al., 2008). Consequently, triathletes rely on their ability to run efficiently without displaying any adverse adaptations to either the preceding cycling leg (acute, short term adaptations) or as a result of their multidisciplinary training regime (chronic, long term adaptations) (Bonacci et al., 2010a; Saunders et al., 2004).

The majority of triathletes, including elite triathletes, report a perceived lack of coordination when running off the bike (Bonacci et al., 2010a; Hausswirth and Brisswalter, 2008; Heiden and Burnett, 2003). A variety of studies have aimed to investigate the occurrence of acute, short term running adaptations post cycling. Cycling immediately prior to running has been found to cause reduced stride length and subsequent increased stride velocity, increased forward trunk lean and altered knee angle in both the swings and stance phase of the running cycle (Hausswirth et al., 1997; Gottschall and Palmer, 2000; Millet and Vleck, 2000 and Millet et al., 2001). Such adaptations to cycling have been linked to compromised running performance within triathlon (Tew, 2005).

Even when running ‘fresh’ (i.e. not off the bike) triathletes display a different running gait to pure runners (Connick, 2009), exhibiting shorter relative strides and decreased hip ROM, thigh extension, hip flexion and anterior pelvic tilt in comparison to runners. The authors propose that these adaptations are brought about as a result of the large volume of cycling typically undertaken by triathletes and the prolonged periods of hip flexion and restricted pelvic movement this causes.

When cycling, triathletes and cyclists aim to improve their aerodynamics by adopting an extremely flexed posture (Callaghan, 2005). In endurance events this requires the hips and knees to be maintained in a flexed position for extremely long durations both in races and training. Large volumes of cycling have been found to result in muscular adaptations that may not be conducive to optimal running performance. The extremely flexed position of cycling means that the mono-articular muscles of the vastii group operate over a much longer range than in running, where knee extension minimises the muscular length required. This causes optimal power generation in this muscle group to occur at much longer lengths in cycling than in running (Salvberg and Meijer, 2003). Similarly maximal biceps femoris strength has been found at shorter lengths in cyclists than in runners (Herzog et al., 1991). Studies examining the relationship between clinical measures of static hip extension capability and hip extension during running have found no correlation between these measures (Schache et al., 2000). However, the participants in this study were pure runners, who exhibited no hip extension restrictions. A consequence of the prolonged periods of extreme flexion encountered by cyclists could be tightening of the hip flexor musculature. As such, cyclists are often encouraged to undertake stretching programmes focused at combating muscular and tendon shortening in this region (Callaghan, 2005). Despite the findings of Schache et al., (2000), it seems plausible that restricted hip extension capability within cyclists may inhibit hip extension during running and could also be a cause of altered hip mechanics in triathletes.

The differing running kinematics between triathletes and runners may therefore be due to musculature adaptations for optimal performance during cycling and rather than running (Connick, 2009). Furthermore, triathletes typically undertake large volumes of cycling training (Gulbin and Gaffney, 1999; O'Toole, 1989) and as such, the link between altered running technique in triathletes and cycling seems a plausible explanation. However this link is yet to be confirmed through the study of pure cyclists. If cycling is the cause of the running technique changes in triathletes, it stands to reason that cyclists will exhibit similar or more exaggerated differences than triathletes when compared to runners.

The triathlete group studied by Connick (2009) was comprised of triathletes who had not trained or competed solely as a runner prior to taking up triathlon. Therefore, an alternative explanation for the differences in running technique between triathletes and runners could be that the triathletes were not as experienced at running as the runners. Subsequently they displayed kinematic differences that were due to skill level and not as a result of the multifaceted nature of triathlon training.

The aim of this study is to therefore examine the effect of running history on running performance in relation to triathlon. This study will examine the running technique of cyclists (no running experience), pure runners (no experience of triathlon), pure triathletes (no previous pure running history) and triathletes who trained and competed purely as runners prior to taking up triathlon. It is hypothesised that the running adaptations previously proposed to be due to the cycling element of triathlon will be present in triathletes and to a larger extent in cyclists. It is also expected that whilst triathletes with a running background may display some adaptations to triathlon, their increased running experience will be evident. As such, the adaptations to triathlon will be less noticeable in this group than in the triathlete group. Furthermore, it is expected that these restrictions will be linked to restrictions in static hip extension measures.

3.3 **Methods**

Participants

A total of 36 male participants took part in this study (9 runners, 9 pure triathletes, 9 triathletes from a running background and 9 cyclists). Participants' characteristics are presented in Table 3.1. Participants had at least 2 years experience of training and competing at their chosen sport, additionally, the triathletes with a running background had 2 years experience of training and competing solely as runners prior to taking up triathlon (within which they also had 2 years experience). All participants were injury free at the time of data collection. All participants provided informed consent and the study was approved by the University ethics committee.

Table 3.1: Participant characteristics (mean ±S.D.) *indicates significant difference to other groups. NB. RunTri Experience a = experience in running; b = experience in triathlon.

	Runners	**Triathletes**	**RunTri**	**Cyclists**
Age (years)	26.6 (8.2)	30.0 (10.5)	28.9 (8.0)	28.7 (9.7)
Height (m)	1.77 (0.03)	1.75 (0.04)	1.82 (0.03)	1.77 (0.04)
Weight (kg)	68.05 (5.87)	68.18 (5.29)	72.53 (3.58)	70.85 (1.94)
Experience (years)	9.8 (4.7)	7.9 (6.6)	a. 9.1 (6.3) b. 6.8 (6.1)	6.2 (5.4)
Weekly cycling (miles)	-	107.5 (50.0)	111.4 (53.3)	140.7* (60.9)
Weekly running (miles)	62.7 (18.5)*	24.75 (10.5)	27.14 (10.8)	-

Data Collection

Each participant visited the lab on one occasion. Lab visits comprised of a warm up and running kinematic tests at 13, 15 and 17km/h, further details of the running kinematics can be found in Chapter 2.

In addition to the running kinematic measures, 5 participants from the cyclist, pure triathlete and runner groups had their hip flexibility measured[1]; this took place immediately following the warm up, prior to running kinematic data collection.

Statistical Analysis

Two-way between subjects ANOVAs with repeated measures were used to establish differences between groups and velocities, with the LSD post-hoc test used to establish where the differences occurred. All statistical analyses were performed in SPSS (v. 15) and the significance level was set to $p<0.05$. Pearson's correlation coefficient was used to examine relationships between static hip flexibility and kinematic measures.

3.4 **Results**

Cyclists exhibited the shortest stride length at every velocity, with measures ranging from 2.33m at 13km/hr to 2.85m at 17km/hr. In comparison, runners' stride length ranged from 2.64m to 3.27m (Figure 3.1).

[1]Flexibilty measures were only taken from these 3 groups, as this part of the analysis was added retrospectively.

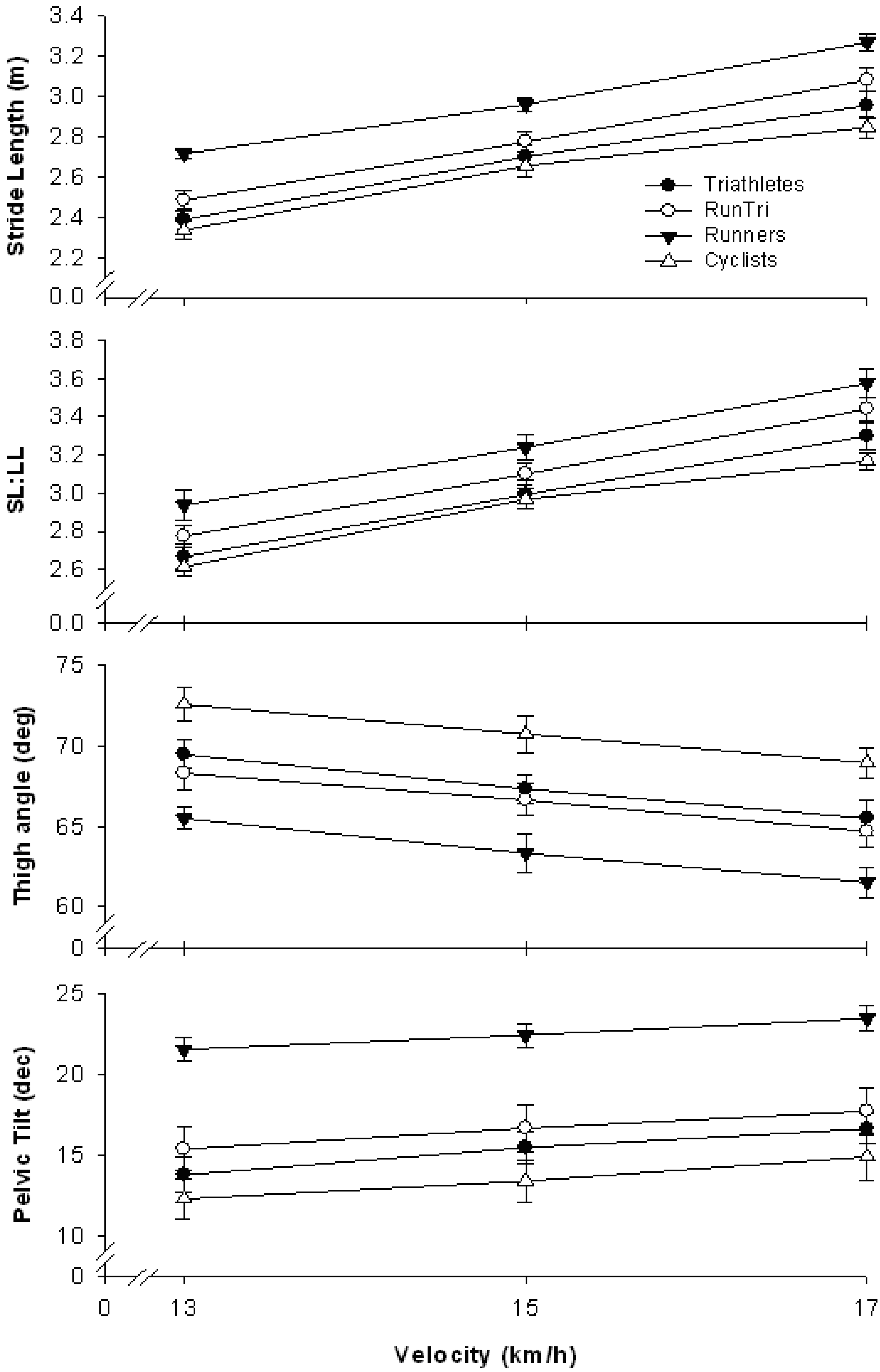

Figure 3.1: The effect of group and velocity on key stride parameters. A) Stride length B) relative stride length ([SL:LL] ± SEM), C) thigh angle (±SEM), C) anterior pelvic tilt (±SEM).

There was a significant main effect of running background on both stride length (SL) [$F(3, 32)=6.67$, $p=0.001$ $\eta^2=0.0.39$], and relative stride length (SL:LL) [$F(3, 32)=8.35$, $p<0.001$ $\eta^2=0.44$]. Post hoc measures showed that runners exhibited significantly longer absolute and relative SL to cyclists (SL $p<0.001$; (SL:LL) $p<0.001$) and pure triathletes (SL $p=0.004$; SL:LL $p=0.002$). Cyclists had significantly shorter absolute and relative stride lengths than triathletes with a running background (SL $p=0.03$; SL:LL $p=0.03$). For both measures there was no significant differences between triathletes and cyclists (SL $p=0.24$ SL:LL $p=0.59$) or triathletes and triathletes with a running background (SL $p=0.30$; SL:LL $p=0.08$).

There was also a significant main effect of velocity for SL[$F(2, 64)=811.51$, $p<0.001$ $\eta^2=0.96$], and SL:LL [$F(2, 64)= 823.30$, $p<0.001$ $\eta^2=0.96$], with post hoc measures showing that significant differences occurred between all velocities ($p<0.01$).

Cyclists exhibited the greatest stride length variability at all velocities. There was no difference in variability between triathletes, triathletes from a running background and runners (Figure 3.2)

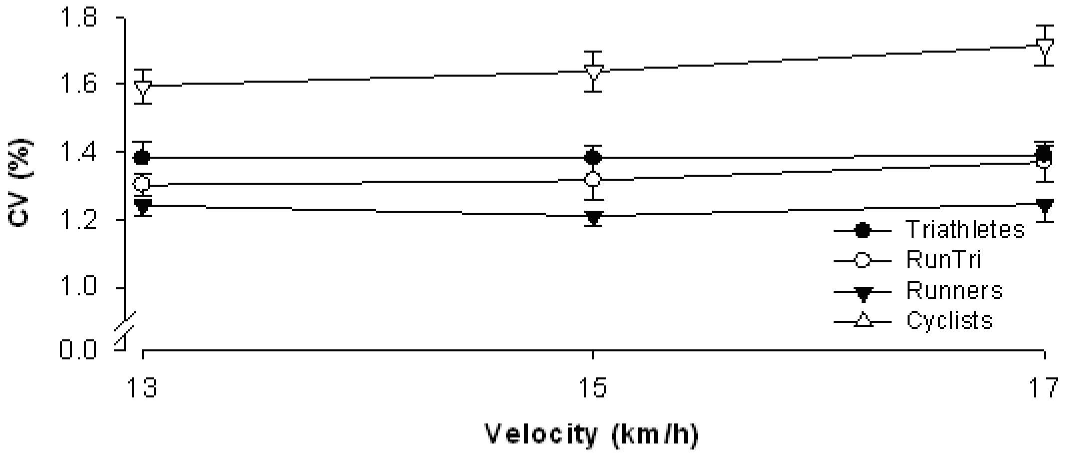

Figure 3.2: Stride length coefficient of variation.

There was a significant main effect of running background on stride length variability [$F(3, 32)=9.18$, $p=0.001$ $\eta^2=0.45$]. Post hoc measures showed that cyclists exhibited significantly greater stride length variability than pure triathletes ($p=0.02$), triathletes with a running background ($p<0.001$) and runners ($p<0.001$). There were no significant differences between any of the other groups.

Similar to the stride length measures, cyclists exhibited least thigh extension (72.61° to 68.97° at 13 and 17km/hr respectively) and runners the most (66.38° to 62.15° at 13 and 17km/hr respectively). Both running background and velocity respectively have a significant main effect on thigh extension ([$F(3, 32)=10.35$, $p=.001$ $\eta^2=0.49$] and [$F(2, 64)=94.69$, $p=.001$ $\eta^2=0.75$]). Post hoc analysis showed runners exhibited greater thigh extension than pure triathletes ($p=0.005$), triathletes with a running background ($p=0.026$) and cyclists ($p=0.001$). Cyclists also displayed significantly less thigh extension than triathletes with a running background ($p=0.003$) and triathletes ($p=0.017$). There was no significant difference in thigh extension between triathletes and triathletes with a running background ($p=0.50$). Post hoc measures also show that the effect of velocity was significant between all velocities ($p<0.01$). As with the aforementioned kinematic results, cyclists demonstrated the least anterior pelvic tilt (12.31° to 14.92° at 13 and 17km/h respectively) and runners the most (21.57° to 23.49° at 13 and 17km/h respectively). There was a significant main effect of running background on pelvic tilt ([$F(3, 32)=6.68$, $p=.001$ $\eta^2=0.39$]) with runners exhibiting significantly greater anterior pelvic tilt than cyclists ($p<0.001$), triathletes with a running background ($p=0.010$) and pure triathletes ($p=0.008$). In contrast to the other kinematic variables presented, post hoc tests showed no significant differences between cyclists and triathletes with a running background (p=0.105) or pure triathletes (p=0.127). There were no significant differences in peak anterior pelvic tilt measures between triathletes and triathletes with a running background. As with the other measures velocity also had a significant effect on anterior pelvic tilt ([F(2, 64)=72.6, p=.001 η^2=0.69]), with post hoc measures showing that these differences were significant between all velocities (p<0.01). Means and standard deviation of additional kinematic variables can be found in Appendix D.

Significant correlations of anterior pelvic tilt and hip extension were found in all of the groups (Figure 3.3).

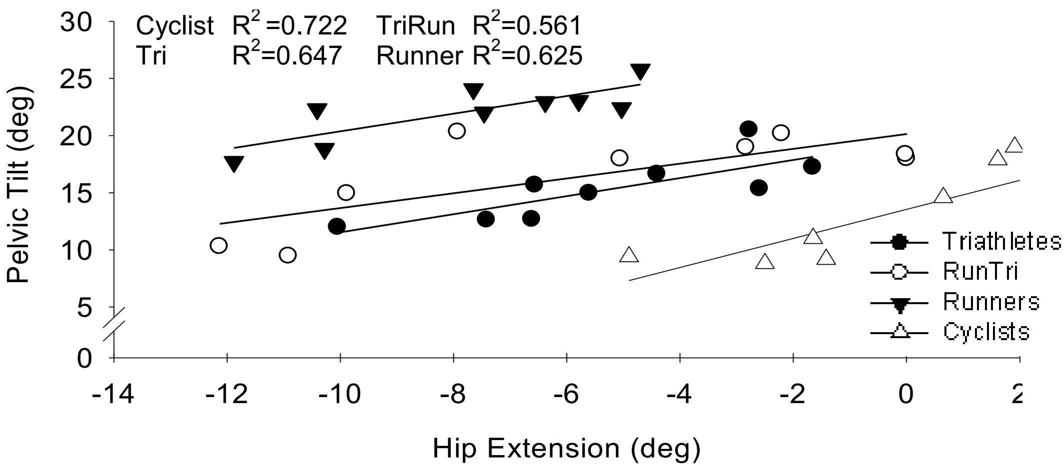

Figure 3.3: Correlation analyses of hip extension and anterior pelvic tilt (+ve hip angle = flexion, -ve = extension).

Effect of Flexibility

Flexibility varied considerably between groups with runners displaying hip extension flexibility of 11.3° compared to the -7.8° of cyclists (Table 3.2). There was an overall significant effect of group on flexibility ([F(2, 15)=29.21, p<0.001 η^2=0.80]).

Table 3.2: Mean flexibility measures in triathletes, runners and cyclists (±SD). *represents significant differences from runners.

	Flexibility (deg)
Cyclists	-7.8 (1.4)*
Pure triathletes	-1.8 (4.6)*
Runners	11.3 (6.5)

Flexibility correlated significantly with stride length and relative stride length in cyclists and triathletes. No such relationship was found between these measures in runners (Table 3.3). No relationship between static hip extension and any other kinematic measure was found.

Table 3.3: Correlation of static hip flexibility and with key kinematic variables at 15km/h. *=significant correlation (p=<0.05).

		SL	**SL:LL**	**HipExt**	**APT**	**ThiExt**
Cyclist	Corr.	**0.681***	**0.697***	0.388	0.144	0.791
	Sig.	**0.009**	**0.001**	0.447	0.786	0.061
Tri	Corr.	**0.687***	**0.604***	-0.273	-0.171	-0.716
	Sig.	**0.008**	**0.010**	0.600	0.746	0.109
Runners	Corr.	0.388	0.299	0.781	0.494	0.818
	Sig.	0.512	0.565	0.067	0.319	0.254

3.5 **Discussion**

The objective of this study was to compare the running kinematics of triathletes, runners, cyclists and triathletes from a running background in order to gain further understanding as to the cause of the previously documented differences between runners and triathletes. In support of the hypothesis, cyclists were found to have the shortest stride length of all the groups tested, displayed the least anterior pelvic tilt and thigh extension. However, the hypothesis regarding the running technique of triathletes from a running background was only partially supported, as pure triathletes and triathletes from a running background displayed no statistically significant differences to one another in all of the measures presented.

Mean stride length of runners across the three velocities of 2.98m compares favourably with previously reported data of 2.96m (Connick, 2009). Mean triathlete stride length in the current study of 2.68m is much shorter than that of 2.86m reported by the aforementioned authors. However, this can be explained by differences in leg length between the participants used in each study; similar measures of stride length relative to leg length between this study (2.98) and that of Connick (2009), (3.02) support this theory. Furthermore, hip, thigh and pelvis kinematic data all compare favourably to the findings of Connick (2009). Measurements of the same parameters in triathletes with a running background fall in between that of previously presented data regarding runners and triathletes (SL 2.79m, SL:LL 3.10). To the authors' knowledge, no data exists on the running technique of pure cyclists to enable comparisons.

The primary aim of this study, to ascertain if the previous assumption of cycling being the cause of running adaptations in triathletes is true, was investigated by comparing the running technique of cyclists to that of triathletes and runners. The significantly smaller stride lengths and relative stride lengths, greater stride rate, decreased thigh extension and anterior pelvic tilt displayed by cyclists and in comparison to both triathletes and runners support this previous assumption.

The extremely flexed position endurance cyclists often adopt (Callaghan, 2005) coupled with the amount of time spent in this position training by both cyclists and triathletes is likely to cause muscular adaptations that may result in a modified running technique. Pertinently, triathletes have been reported to undertake greater volumes of cycling training than running (O'Toole, 1989; Gulbin and Gaffney, 1999). It therefore seems likely that triathletes could have musculature adapted to cycling rather than running. This is supported by findings in the current study which demonstrate that cyclists' running technique differs from that of runners, within the same variables as triathletes'. Furthermore, these differences are more exaggerated between runners and cyclists than between runners and triathletes.

Pelvic tilt has been found to increase with velocity (Novacheck, 1998) and it has been postulated that such a mechanism, together with increased hip extension, enables horizontal propulsive forces to be translated along the transverse axis of the leg in a more efficient horizontal direction (Chang and Kram, 1999; Chang et al., 2000; Novacheck, 1998). Restrictions in both of these measures in triathletes and cyclists are likely to cause a more vertical direction of force application, resulting in less economical running style.

Maximum stride rate has been found to be similar in runners with differing peak velocities (Weyand et al., 2000). Furthermore, runners' stride length has been found to plateau at 6.6m/s (24km/h) and subsequent increases in velocity are due to increased stride frequency (Weyand et al., 2000). The shorter strides and therefore a greater stride rate for a given velocity in both triathletes and cyclists, when compared to runners, imply these groups are liable to reach peak stride rate and subsequently peak velocity earlier than runners. Closer inspection of Figure 3.1 shows that at between 15km/h and 17km/h the stride length of cyclists does not increase at the same rate as that of triathletes and runners. This may be an indication of stride length beginning to plateau in cyclists and stride rate becoming the dominant determinant of velocity. However, without analysis of further velocities, this is difficult to confirm.

The effect of different running ability between groups and its effect on key running parameters cannot be ignored completely as a possible explanation for the reported differences. Indeed, it has been reported that biomechanical variables could account for up to 54% of variation in running ability (Williams and Cavanagh, 1987). When examining the running technique of cyclists (a group not trained for running) it is difficult to exclude ability as a potential variable. The large intra-participant variability (an indicator of skill level) reported within cyclists, indicates that the cyclists within this study were not as skilled at running as the other groups (Figure 3.2). Furthermore, differences may exist in the anthropometry of each group, for example cyclists may exhibit greater thigh circumference than runners. Such differences may in turn affect joint range of motion, resulting in different running techniques. Future studies may seek to address this by including strength, flexibility and anthropometric measures applicable to both running and cycling to provide further information regarding potential factors that may inhibit running.

In order to minimise any potential effects of fatigue, running bouts of 2 minutes were used for data collection. However, given the range of running experience, the use of the same velocities for each group may have resulted in differing levels of fatigue between groups and in turn have caused changes in their running kinematics. Future studies could seek to address this issue by allowing participants to either run at a self selected velocity or at a velocity relative to maximum velocity.

This study also analysed the impact of prior running experience on the running technique of triathletes. In partial agreement to the hypothesis, triathletes with a running background did demonstrate adaptations to triathlon and their running kinematics were significantly different to that of runners. The potential causes and effects of these changes have already been discussed at length in relation to the running kinematics of pure triathletes. In partial disagreement to the hypothesis, triathletes with a running background demonstrated no differences to triathletes. Based on the premise that when turning to triathlon, pure runners would demonstrate greater running ability than their pure triathlete counterparts, it was anticipated that triathletes with a running background would sit somewhere in between runners and triathletes in terms of running kinematics. However, this was not the case. This lack of difference between triathletes and triathletes from a running background could be attributed to either the volume of cycling undertaken by runners who take up triathlon, or as a result of the recruitment criteria set out in this study for triathletes with a running background.

It seems intuitive that when taking up triathlon, experienced runners would chose to focus on their cycling and swimming ability rather than running in which they have already spent many years perfecting. Subsequently the improved running technique could quickly be overturned by musculature adaptations to the combined sport of triathlon. Furthermore, given that elite triathletes have shown smaller scale running modifications immediately proceeding cycling than sub-elites (Millet et al., 2000), it follows that runners who are completely inexperienced at cycling may show large adaptations to cycling when taking up triathlon.

The recruitment criteria of triathletes with a running background in this study was that participants had at least two years experience as a pure runner prior to turning to triathlon and subsequently has two years experience as a triathlete. Setting such criteria, particularly in relation to triathlon experience meant that there was large range of both running experience and triathlon experience amongst the triathletes with a running background in this study (3-20 years). Given that it is known that cycling causes adaptations to running technique it is possible that participants with less triathlon experience may still display running technique similar to that of runners and vice versa. Analysing, longitudinally, the adaptations of runners who take up triathlon may unearth some important details of the chronic impact of cycling upon running kinematics.

Further analysis in a small selection of participants from the cyclist, triathlete and runner groups sought to address the impact of cycling on hip extension flexibility. Correlation analyses were also carried out to asses what relationship these flexibility measures had with key running parameters.

Both cyclists and triathletes demonstrated significantly lower hip extension flexibility than runners. In contrast to findings of Schache et al., (2000) who found no relationship between hip extension capability in runners and running parameters, static hip extension was significantly related to stride length and relative stride length in cyclists and triathletes. The most likely explanation of this discrepancy is the difference in participant flexibility between runners in their study and the mixture of participants in the current study. The participants in the study of Schache et al., (2000) were all experienced runners and the peak measures of hip extension flexibility of 17.4° they present, whilst comparable to runners in our study (11.3°), are substantially greater than in the cyclists and triathletes in the current study who were unable to reach hip extension (triathletes -1.8°; cyclists -7.8°).

The restricted flexibility found in cyclists and triathletes also supports the idea that cycling may, in some way, restrict movement of the hip and pelvis, which in turn leads to changes in running kinematics. Further analyses of flexibility in groups who undertake training that is likely to inhibit flexibility is warranted. Although these data offer some insight as to the impact of extremely reduced flexibility on running kinematics, extreme caution must be adopted when analysing these findings as they are based on extremely small participant numbers.

Future studies could seek to establish whether interventions to overcome the effect of cycling improve the running ability triathletes and the effect such *corrections* have on cycling and overall triathlon ability.

In summary, of the four groups tested, cyclists exhibit running kinematics that differ the most from runners. As these differences occur in the same parameters as when triathletes are compared to runners, it is likely that the volume of cycling undertaken by triathletes is the cause of the differences. Triathletes from a running background also exhibit differences in running kinematics when compared to runners but not in comparison to triathletes. It seems that training as a runner prior to taking up triathlon does not prevent modifications to running technique. It is yet to be established if this is due to a greater concentration on cycling by triathletes with a running background or an inevitable side effect that occurs in all triathletes. Furthermore, the timescale of these adaptations is yet to have been examined.

Measurement of hip extension flexibility in this study highlights the relationship of these clinical measures to performance variables in participants with restricted flexibility. Further research to assess whether increased static flexibility allows triathletes (and cyclists) to run more like runners, and whether this is necessary to improve triathlon performance is warranted.

Chapter 4: FEMALE TRIATHLETE STRIDE PARAMETERS AND RUNNING KINEMATICS IN COMPARISON TO RUNNERS

4.1 Abstract

Long-term adaptations in running kinematics have been found to occur in male triathletes, most likely due to the multi-disciplinary training undertaken. Specifically, it appears that the volume of cycling training undertaken by triathletes results in restricted movements within the pelvic and hip region of triathletes. However, previously documented gender differences running and cycling technique indicate that these findings should not be directly extrapolated to female populations. Therefore the aim of this study was to examine the differences between female runners and triathletes during running.

Twenty-one female participants (10 triathletes and 11 runners) performed 3x2 minute bouts of treadmill running at randomly assigned speeds of 11km/h, 13km/h and 15km/r. During this time, 3D kinematic data was captured.

Triathletes exhibited significantly shorter absolute and relative strides in comparison to runners. Furthermore, triathletes demonstrated restricted movement within the pelvic and hip region, displaying significantly less hip and thigh extension and pelvic tilt than runners.

It is concluded that the restricted running movement demonstrated by male triathletes in response to the volume of cycling training undertaken is replicated in females. Given that this occurs irrespective of previously published gender differences in both cycling and running, this finding adds further support to the postulated link between cycling training and impaired running technique in triathletes.

4.2 Introduction

The aetiology of injuries suffered by females appears to be different to those in males (Schache et al., 2003; Ferber et al., 2003). Differences between the running kinematics of males and females are thought, in part, to explain such gender differences and consequently a number of studies have sought to investigate the running kinematics of males and females (Chumanov et al., 2008; Schache et al., 2003; Ferber et al., 2003; Malinzak et al., 2001; Williams et al., 1987).

In the non-sagittal planes, females exhibit greater peak hip internal rotation and adduction (Ferber et al., 2003; Chumanov et al., 2008) and greater peak knee abduction (Ferber et al., 2003; Malinzik et al., 2001) than males. Additionally, females demonstrate greater peak-to-peak joint rotations in all planes in the lumbo-pelvic-hip complex apart from in pelvic tilt; in this parameter females exhibited an offset of approximately 4° greater than their male counterparts (Schache et al., 2003).

Gender differences in anthropometric measures and the difference in spatio-temporal parameters of running gait of males and females have been speculated to be the underlying cause of such differences (Ferber et al., 2003; Schache et al., 2003). However, when these factors were taken in to account, the only anthropometric variable found to be a significant predictor of joint angular rotations of the lumbo-pelvic-hip region during running was standing pelvic tilt (Schache et al., 2003). Moreover, the same authors report that even though several spatio-temporal parameters were also found to be predictors of specific angular rotations, the most common variable related to the differing magnitudes of joint rotations was gender.

In contrast to the volume of comparative studies of male and female gait kinematics, gender differences in cycling kinematics have received limited attention. One such study found that female cyclists exhibit more anterior pelvic tilt than males, particularly when in the ‘drops’ hand position (Sauer et al., 2007). This has been related to gender differences in saddle pressure; females exhibit greater changes in anterior force, maximum anterior pressure and posterior centres of pressure (Potter et al., 2008). As with running studies, it has been speculated that the cause of these gender differences may be the fundamental, anthropometric differences in male and female pelvis geometry (Sauer et al., 2007; Potter et al., 2008).

The sport of triathlon is formed by sequential swimming, cycling and running and to win, triathletes rely on their ability to run efficiently without displaying any adverse, acute adaptations to the preceding cycling leg or more long term, chronic adaptations to their multidisciplinary training regime (Bonacci et al., 2010b; Saunders et al., 2004). Many studies have examined both the short term (Hausswirth et al., 1997; Gottschall and Palmer, 2000; Millet and Vleck, 2000 and Millet et al., 2001) and long term (Connick, 2009) running adaptations to triathlon (described in detail in Chapters 1 and 3 of this thesis). However, a major limitation of the aforementioned studies involving triathletes is that they have focused solely on adaptations and technique differences between male cohorts. Given the differences between male and females, in both cycling and running, findings based on a male population should not be directly extrapolated to a female population. Moreover, many of these gender differences appear to occur within similar regions that adaptations to triathlon and cycling do.

It is therefore the aim of this study to evaluate the differences between female runners and triathletes during running. It is hypothesised that female triathletes will exhibit decreased pelvic and hip motion, which will in turn decrease stride length and increase stride frequency in comparison to pure runners. However, as a result of the previously documented gender differences in pelvic tilt during cycling, it is predicted that the differences found between female runners and triathletes will not be of the same magnitude as in males.

4.3 **Methods**

A total of 21 female participants took part in this study (11 runners, 10 triathletes). Participant characteristics are presented in Table 4.1. All participants were healthy and uninjured at the time of testing and had trained at least 3 times a week for the last 2 years. They had at least 2 years experience of training and competing and were experienced at treadmill running. Additionally triathletes had not previously trained exclusively as runners before taking up triathlon. The study was approved by University ethics committee and all participants provided written informed consent.

Table 4.1: Participant characteristics (mean ±S.D.)

	Runners	**Triathletes**
Age (years)	22.91 (3.88)	22.00 (4.60)
Leg Length (m)	0.82 (0.04)	0.88 (0.04)
Weight (kg)	60.20 (8.14)	65.33 (9.71)
Experience (years)	7.18 (3.31)	5.40 (3.06)
10k PB (mins)	43:11 (4:30)	45:05 (5:21)

Participants visited the lab on one occasion, during which time motion data was collected at 3 different velocities (11km/h, 13km/h and 17km/h). Details of motion capture and data processing can be found in Chapter 2.

Statistical Analysis

Two-way between subjects ANOVAs with repeated measures for running velocity were used to test for differences between groups and velocities. Prior to these tests, Maulchy's test of spherecity was conducted. In instances where a significant lack of homogeneity of variance was indicated, Greenhouse-Geisser corrections were utilised. Pearson's correlation coefficient was used to determine relationships between various stride parameters and kinematic measures. The significance level for all statistical calculations was set at $\alpha=0.05$.

4.4 **Results**

There was a significant main effect of running background on relative stride length (SL:LL) [$F(1, 19)=5.482$, $p=0.001$ $\eta^2=0.224$]. Triathletes exhibited shorter relative strides at 11km/h (2.41m SD 0.08), 13km/h (2.80m SD 0.13) and 15km/h (3.05m SD 0.15) than runners (2.51m SD 0.15 [11km/h]; 2.88m SD 0.16 [13km/h]; 3.20m SD 0.16 [15km/h]) (Figure 4.1).

Running background also had a significant main effect on thigh extension [$F(1, 19)=12.047$, $p=0.003$ $\eta^2=0.38$], hip extension [$F(1,19)=5.985$, $p=0.024$ $\eta^2=0.24$] and anterior pelvic tilt [$F(1,19)=4.693$, $p=0.043$ $\eta^2=0.20$].

All measures increased in a linear fashion relative to velocity in both triathletes and runners (Figure 4.1). The effect of velocity was significant in stride length (SL) $F(1.28,24.31)=26.074$, $p<0.001$ $\eta^2=0.96$], SL:LL [$F(1.35,25.56)=28.673$, $p<0.001$ $\eta^2=0.97$], thigh extension [$F(1.47,27.96)=36.120$, $p<0.001$ $\eta^2=0.655$], hip extension [$F(1.508, 24.80)=26.074$, $p<0.001$ $\eta^2=0.570$] and pelvic tilt [$F(2, 38)=29.610$, $p<0.001$ $\eta^2=0.61$]. Means and standard deviation of additional kinematic variables can be found in Appendix D.

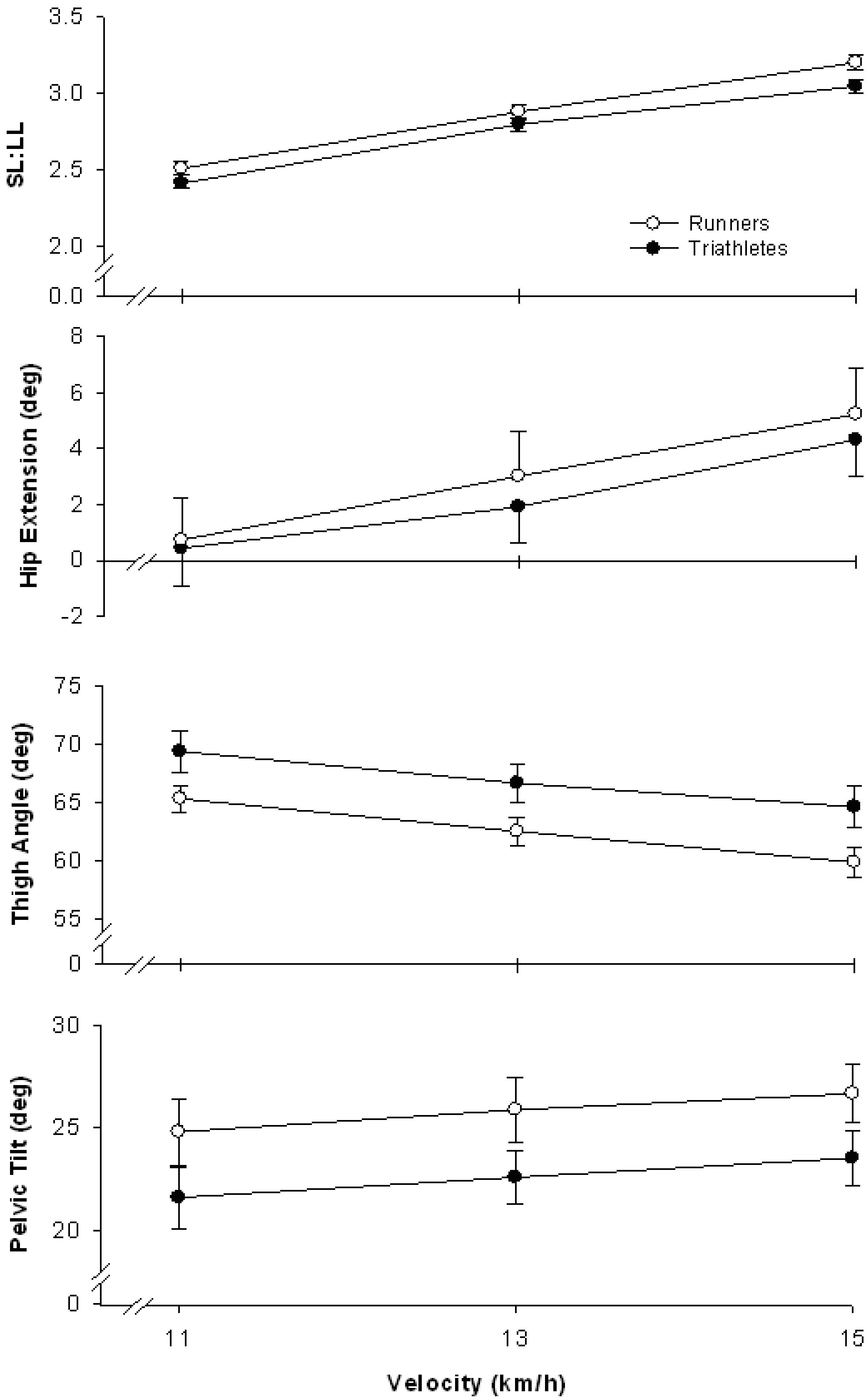

Figure 4.1: The effect of group and velocity on A) relative stride length (±SEM), B) Hip Extension, C) thigh angle (±SEM) and D) anterior pelvic tilt (±SEM).

Significant correlations of anterior pelvic tilt and hip extension were found in runners and triathletes both when considered both in unison and combined (Table 4.3 and Figure 4.2).

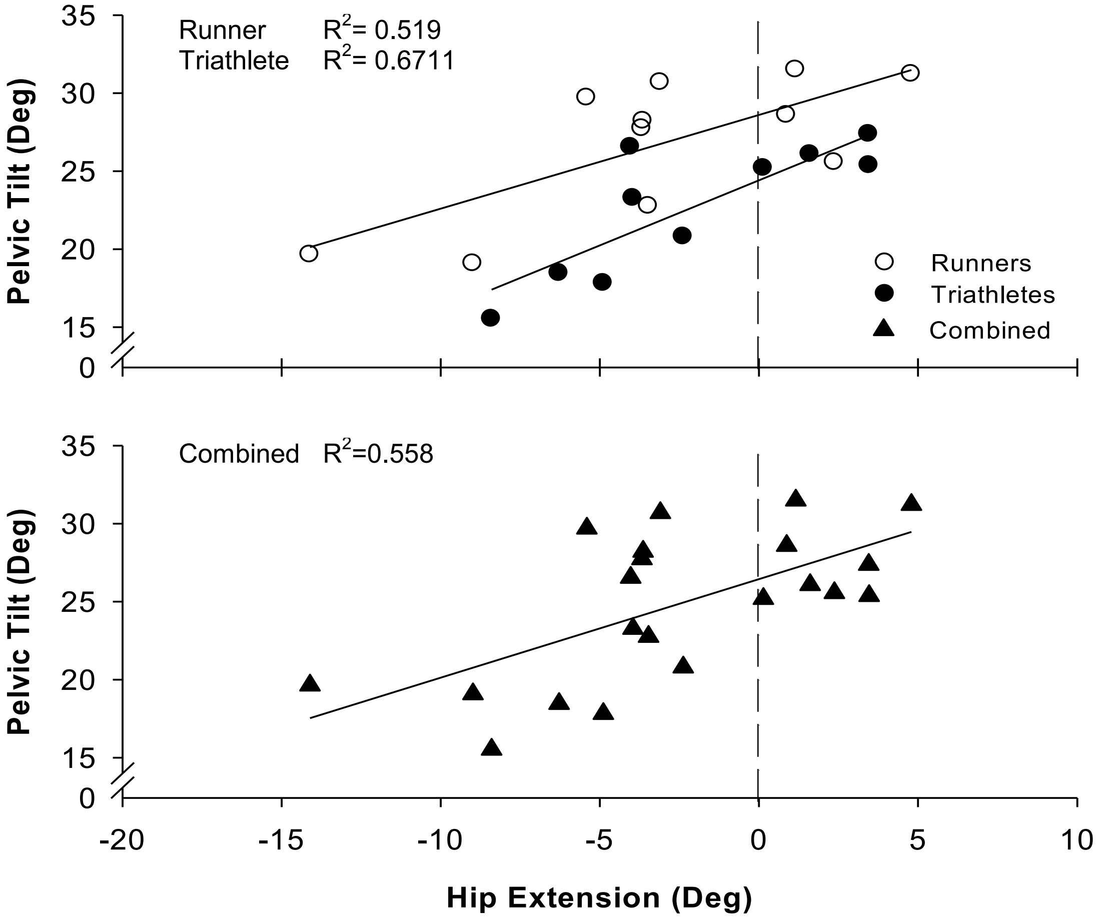

Figure 4.2: Correlation analyses of hip extension angle and anterior pelvic tilt angle. +ve hip angle = flexion, -ve hip angle = extension.

The correlation matrix for all participants is presented in Table 4.3. There was a significant negative correlation between thigh extension and stride length, and thigh extension and pelvic tilt.

Table 4.2: Correlation matrix for key kinematic variables at 13km/h. Pearson's coefficients are presented in the non shaded area (*=significant correlation), significance values are presented in the shaded area.

	Stride Length	SL:LL	Stride Rate	Thigh Ext	Hip Ext	Pelvic Tilt
Stride Length		**0.513***	**-0.979***	**-0.4 59***	-0.303	0.151
SL:LL	**0.009**		**0.500***	-0.192	0.347	-0.049
Stride Rate	**<0.001**	**<0.001**		0.361	0.286	-0138
Thigh Ext	**0.060**	0.202	0.054		0.060	**-0.384***
Hip Ext	0.091	0.061	0.104	0.398		**-0.558***
Pelvic Tilt	0.256	0.416	0.275	**0.043**	**0.004**	

Participants who exhibited the least pelvic tilt exhibited increased hip extension. Increased pelvic tilt resulted in increased stride thigh extension which, in turn led to increased stride length.

4.5 Discussion

This study was carried out in order to investigate whether the apparent training adaptations observed in males as a result of triathlon training, also occur in females. In support of the main hypothesis, female triathletes were found to exhibit shorter relative stride lengths and decreased hip, thigh and pelvic angles when compared to female runners.

Mean female runner stride length of 2.53m (13km/h) and 2.82m (15km/h) compares favourably to that previously found in runners of 2.63 at 14.4km/h (Schache et al., 2003). Mean female triathlete stride length found in the current study of 2.51m (13km/h) and 2.74m (15km/h) is considerably shorter than the male triathletes (2.88m at 13km/h; 3.15m at 15km/h) tested by Connick, (2009). However, in line with findings reported by Schache et al., (2003), minimal gender differences were found when stride length findings in the current study and the findings of Connick (2009) were expressed relative to leg length (13km/h: males 2.70, females 2.80; 15km/h: males 3.04; females 3.05).

To the authors' knowledge, this is the first study to compare the stride parameters and running kinematics of female triathletes to those of female runners. In a similar study conducted within males, triathletes were found to exhibit shorter relative strides, less hip ROM, decreased thigh extension and limited pelvic tilt in comparison to runners (Connick, 2009), a finding replicated in the current study in a female population. Given the previously documented gender differences in both running (Chumanov et al., 2008; Schache et al., 2003; Ferber et al., 2003; Malinzak et al., 2001; Williams et al., 1987), and cycling technique (Potter et al., 2008; Sauer et al., 2007), it was hypothesised that the differences between female triathletes and runners may not be the same as in males. However, this was not found to be the case.

In males, the volume of cycling training coupled with the extremely flexed posture of cycling (Callaghan, 2005) has been postulated to be cause of the differences exhibited between triathletes and runners. Furthermore, findings in the subsequent study of the running gait of cyclists in comparison to both runners and triathletes agree with this mechanism (Chapter 3). The current study indicates that such a mechanism may be true in female triathletes. This finding adds further weight to the suggested link between cycling and running technique as it occurs irrespective of the aforementioned gender differences in the two disciplines of running and cycling.

Pelvic tilt has been found to increase with velocity (Novacheck, 1998) and it has been postulated that such a mechanism, together with hip extension, enables horizontal propulsive forces to be translated along the transverse axis of the leg in a more efficient horizontal direction (Chang and Kram, 1999; Chang et al., 2000; Novacheck, 1998). Restrictions in both of these measures that have been documented previously in male triathletes have now been shown to occur in females. Such movement patterns are likely to cause a more vertical direction of force application, resulting in less economical running style.

The possibility of cycling inhibiting hip extension flexibility has been addressed previously in males (Chapter 3). Given that similar differences are presented in the current study between female triathletes and female runners as have been previously found between male triathletes and male runners, it seems reasonable to believe that female triathletes may experience a similar lack of hip extension flexibility. Further analyses of flexibility is warranted in both male and female groups who undertake training that is likely to inhibit this.

In comparison to the findings of Connick (2009), females demonstrate greater thigh extension (13 km/h 66.67°; 15km/h 62.54°) and greater anterior pelvic tilt (13 km/h 22.57°; 15km/h 25.87°) than their male counterparts ([thigh extension 13km/h 70.40°; 15 km/h 60.56] [pelvic tilt 13 km/h 15.2°, 23.50°]). Similar gender differences found in the frontal plane have previously been linked to the disparities between the types of running injury suffered by males and females (Ferber et al., 2003). Triathlon training appears to further exacerbate some of the previously documented gender differences in sagittal plane measures. It is possible that modified running technique in both male and female triathletes may result in injuries of differing aetiology to their running counterparts. For instance male triathletes may be more susceptible to injuries typically seen in female runners rather than those in male runners. In respect to these suggestions, more research into the links between multidisciplinary training (such as that undertaken by triathletes), gender and injury aetiology is recommended.

Future studies may seek to establish whether interventions to overcome the effect of cycling improve the running ability triathletes and the effect such *corrections* have on cycling and overall triathlon ability. Furthermore, given the similar nature of the adaptations to triathlon irrespective of gender, programmes designed to modify running technique in triathletes could be aimed at both males and females.

Although some important findings as to the long term adaptations to triathlon in females have been presented, it is pertinent to consider some of the limitations of this study. Observations in this study were limited to the sagittal plane movements of the pelvis and hip. Based on previously documented differences between triathletes and runners, and the relation of movements in this plane in both cycling and running, this was a deliberate component of the methods. However the authors' do acknowledge differences in the both the frontal and coronal plane may exist and could provide further information regarding injury susceptibility of female triathletes in particular.

In conclusion, the findings of this study indicate that in spite of gender-specific technique differences in the component parts of triathlon, the same differences exist between female runners and triathletes as are previously documented in males. Such a finding adds further support to the hypothesis that such adaptations are due to long term adaptations to the multifaceted nature of triathlon. Whilst these adaptations are potentially detrimental to performances in the running discipline of triathlon, the affect they have on overall triathlon performance is yet to be ascertained. Given the similar nature of the adaptations, studies that look to modify the technique of triathletes could include female participants alongside males.

Chapter 5: HIP FLEXIBILITY IN TRIATHLON

5.1 Abstract

When compared to runners, triathletes exhibit decreased stride length, hip range of motion (ROM) and thigh extension during running. The cycling training undertaken by triathletes, is carried out in a relatively flexed posture, and could result in a shortening of the hip flexors. Subsequently this may account for the observed reduced static and dynamic hip ROM found in triathletes. It is well publicised that static ROM can be increased by a flexibility programme. Therefore the aim of this study was to test whether increasing static hip ROM will elicit changes in running kinematics.

Nine male triathletes completed an 8-week flexibility programme specifically targeting the hip flexors. At -4, 0, 4 and 8-weeks, static hip ROM and running kinematic data were collected at 13, 15 and 17km/h. Between the two baseline measures (Weeks -4 and 0), no differences were found in static hip ROM or running kinematic measures. Significant improvements in the static hip ROM between baseline and weeks 4 and 8, showed that the intervention was successful. However this did not result in significant changes to the running kinematics (stride length, thigh extension, dynamic hip ROM and pelvic tilt).

It is concluded that flexibility alone is not sufficient to change running technique in triathletes and that flexibility programmes should be complemented by specific training.

5.2 Introduction

It has been postulated (Chapters 1, 3 and 4; Connick, 2009) that long term adaptations in triathletes' running technique maybe due to the extremely flexed posture position endurance cyclists often adopt to maximise their aerodynamics (Callaghan, 2005). A consequence of the combined effect of cycling training (Gulbin and Gaffney, 1999; O'Toole, 1989) and the flexed position the hips and pelvis are maintained in could be an adaptive shortening of the hip flexor musculature and a restriction in pelvic motion. Pertinent to triathlon, such a shortening of the hip flexor musculature may reduce hip extension capability during running and consequently reduce stride length.

During endurance events, maximal running performance is affected by both aerobic and biomechanical factors (Slawinski and Billat, 2004). Anterior pelvic tilt has been found to increase with velocity (Novacheck, 1998) and it has been postulated that such a mechanism, together with increased hip extension, enables horizontal propulsive forces to be translated along the transverse axis of the leg in a more efficient horizontal direction (Chang and Kram, 1999; Chang et al., 2000). Altering running gait to allow greater horizontal force generation at no extra energetic cost could therefore enhance performance. However, a potentially detrimental side effect of increased anterior pelvic is that it is coordinated with increased lumbar lordosis and could subsequently cause lower back pain (Schache et al., 2002). Therefore the most effective way of redirecting the ground reaction force in a more horizontal direction may be to increase the amount of hip extension triathletes utilise during running.

Hip flexor stretching programmes have been widely reported as being an effective intervention for increasing stride length in groups who are predisposed to reductions in stride length, such as the elderly (DiBenedetto et al., 2005; Christiansen, 2008; Watt et al., 2009). Additionally, both static and active stretching have also been found to be effective at increasing hip extension (Winters, 2004). However, there are mixed reports as to the effect of flexibility on running economy with some authors reporting a negative effect (Gleim et al., 1990; Craib et al., 1996) and others reporting a positive effect (Godges et al., 1989). Specifically, 47% of running economy variance was explained by external hip rotation and dorsi-flexion flexibility, with participants who demonstrated the least flexibility exhibiting the greatest running economy (Craib et al., 1996). However, flexibility measures taken in this study did not demonstrate any restriction in their flexibility capability. Conversely, in a group of moderately trained runners, oxygen consumption decreased by approximately 2ml/kg/min over a range of velocities after an acute bout of static stretching that increased both hip flexion and hip extension (Godges et al., 1989). However, these findings may be compromised as statistical analyses included both genders irrespective of the potential flexibility and running economy differences between them.

The aim of this study is therefore to investigate the effects, in triathletes, of a hip flexibility programme on static hip flexibility and running kinematics. It is hypothesised that a structured flexibility programme will increase static and active hip and thigh extension, and that this will be coupled with increased in stride length.

5.3 Methods

Eleven male participants volunteered to take part in this study (age 27 ± 9.59 years (SD), height 1.80 ± 0.68m, weight 75.25 ± 8.15kg). All participants trained at least three times a week and competed in triathlon recreationally for 2 years and had not previously trained exclusively as runners. All participants were injury free at the time of testing and the study was approved by the university ethics committee and participants provided written informed consent.

A within-participant, repeated measures study approach was used. Participants visited the laboratory on 4 occasions (Baseline 1 [Week-4], Baseline 2 [Week 0], Mid-intervention [Week 4], Post-intervention [Week 8]) during which static hip flexibility measures and running kinematic data were collected at 13, 15 and 17 km/h (further details are presented in Chapter 2). Between the laboratory visits pre-intervention, mid-intervention, post-intervention, participants carried out an 8 week flexibility intervention programme (Table 5.1). All data collection took place during the participants' off-season.

Table 5.1: Study timeline. Following a 4-week baseline period, participants undertook an 8-week flexibility intervention.

	Time	Procedures
Baseline	Week -4 (pre-baseline)	Static Hip ROM Running Kinematics
	Week 0 (pre-intervention)	Static Hip ROM Running Kinematics
Intervention	Week 4 (mid-intervention)	Static Hip ROM Running Kinematics
	Week 8 (post-intervention)	Static Hip ROM Running Kinematics

Flexibility Intervention

Between weeks 0 and 8 participants were prescribed a bilateral hip flexibility programme, designed by a qualified physiotherapist and using the passive stretches previously documented by Winters et al., (2004). This was carried out 3 times a week on non-consecutive days; details of the specific exercises can be seen in Figure 5.1. All stretches were maintained for 30 seconds on each leg (Winters et al., 2004) and repeated 5 times.

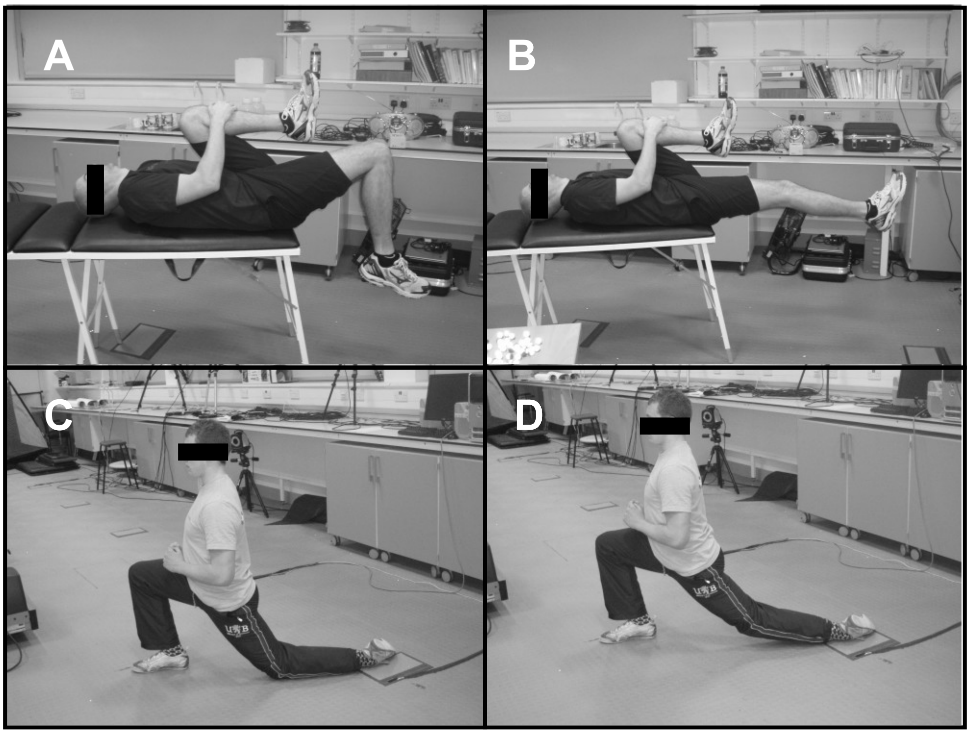

Figure 5.1: Stretches performed throughout the flexibility intervention period. Initially the participants were instructed to perform exercises A, B and C. When the experimenters deemed the participants were proficient at the initial exercises (based on their ability to perform the exercises and the amount of stretch they reported feeling during the exercise) their programme was advanced by using progressions of exercise C, either by straightening the knee of the stretched leg (D) and incorporating holding the arms above the head or reaching across to the opposite side of the body to increase the stretch felt across the hip.

The initial flexibility session took place in the laboratory with instruction, demonstration, feedback and monitoring from the experimenters, ensuring that participants were aware of the correct technique for each stretch. Participants were provided with a training manual with details of the exercises and a training diary to record when they performed the stretched and any comments they had about the session. In addition an experimenter was present for one flexibility session per week. This enabled the experimenters to correct exercise technique if necessary, maintain participant motivation and advise the participants when to progress through the exercise programme.

Statistical Analysis

Two-way repeated measures ANOVAs were used for establishing the effect of time on the static hip ROM measures and kinematic measures. Prior to these tests, Maulchy's test of sphericity was conducted. In instances where a significant lack of homogeneity of variance was indicated, Greenhouse-Geisser corrections were utilised. An LSD post hoc test was used to ascertain between which times the differences occurred. Pearson's correlation coefficient was used to ascertain relationships between variables. The significance level was set at $\alpha=0.05$.

5.4 **Results**

Of the 11 participants recruited, 9 completed the full study (their data are presented hereafter), with 1 withdrawing due to a calf injury during the control period and the other due to personal circumstances. Overall adherence to the flexibility programme was good, with 94% of all sessions completed. Furthermore, 33% of all sessions were supervised by the experimenters.

Results show that the flexibility programme was effective at increasing static hip extension, with both the iliopsoas (IP) and rectus femoris (RF) measures increasing over the 8 week period by 12.7° and 8.5° respectively (Figure 5.2). Tight hip flexor muscles result in the inability to position the leg in a horizontal position when in the modified Thomas test position. Baseline static extension measures of the IP (-4°) and the RF (-18°) show that the participants in this study were unable to achieve this position prior to the flexibility intervention.

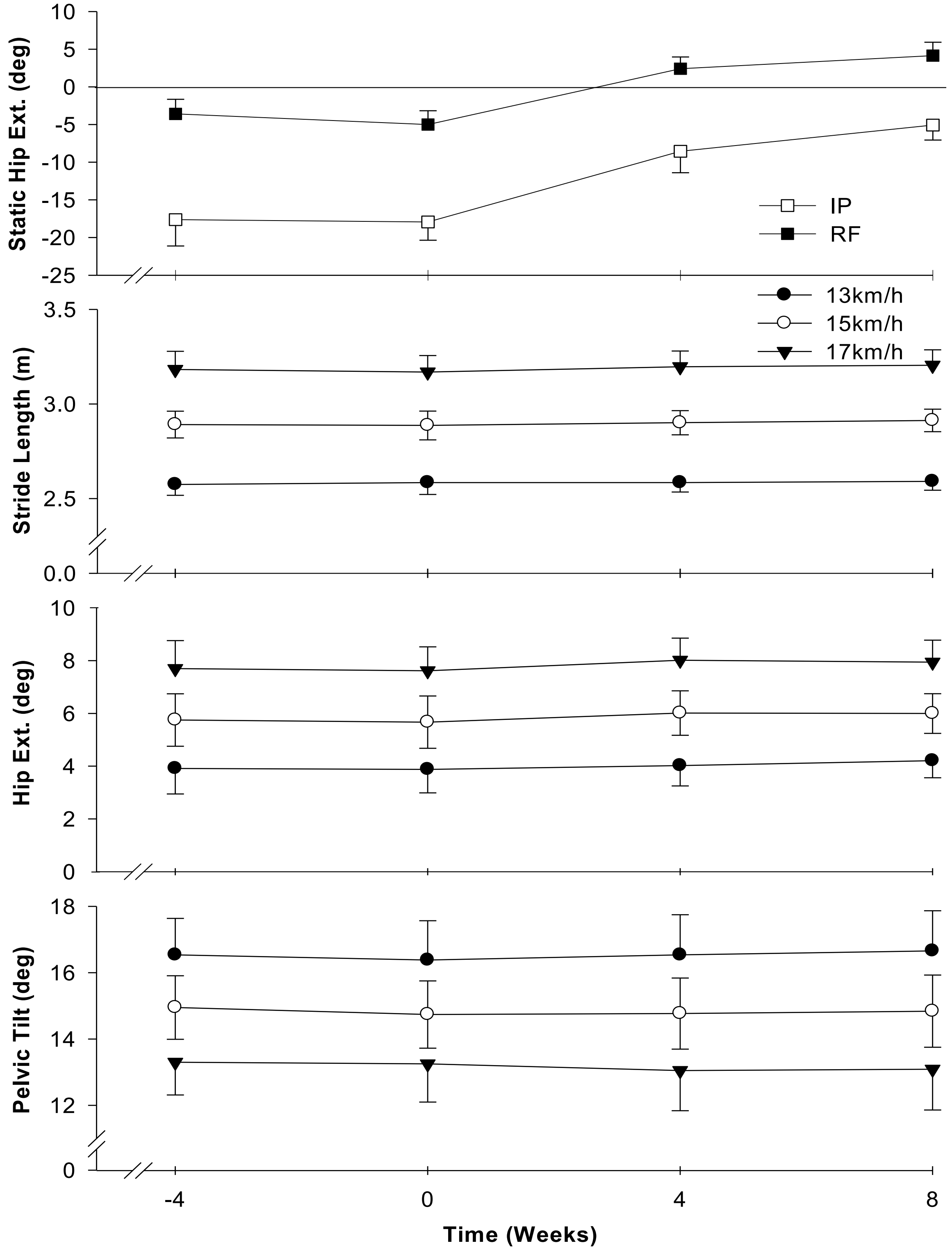

Figure 5.2: The effect of time and velocity on A) static hip flexibility (±SEM), B) stride length (±SEM), C) hip extension (±SEM) and D) pelvic tilt (±SEM) over the 12 weeks (IP = iliopsoas, RF = rectus femoris). Control period (no intervention) weeks -4 to 0, Intervention period weeks 0 to 8.

There was a significant main effect of time and hip flexibility for both the IP [F(3, 15)=26.69, p=.001, η^2=0.84] and RF [F(3, 15)=13.36, p=.001, η^2=0.728]. Post hoc analysis shows that these differences did not occur during the control period (Week -4 to Week 0) for either measure, nor between exercise period measures (Week 4 and Week 8) for either measure. However there were significant differences for both measures between week-4 and weeks 4 (IP p<0.01; RF p<0.01) and 8 (IP p<0.01; RF p<0.01), and between week 0 and weeks 4 (IP p<0.01; RF p<0.01) and 8 (IP p<0.01; RF p<0.01).

Despite the significant increase in static hip flexibility, stride parameter and joint kinematic measures remained relatively constant throughout the study as there was no main effect of time on these measures, SL [F(3, 24)=0.41, p=0.75, η^2=0.49]; SR [F(3, 24)=2.19, p=0.12, η^2=0.22]; hip extension [F(3, 24)=0.95, p=0.95, η^2=0.12]; hip ROM [F(1.47, 11.72)=2.40, p=0.14, η^2 =0.23]; thigh extension [F(3, 24)=1.49, p=0.24, η^2=0.16] or anterior pelvic tilt [F(3, 24)=0.68, p=0.59, η^2=0.075] (Figure 5.2). Means and standard deviation of additional kinematic variables can be found in Appendix D.

Correlation analyses show that baseline static flexibility is not correlated with stride length. However it did have a significant negative relationship with changes in stride length (R^2 =0.892; p=0.001) active hip extension (R^2 =-0.646; p=0.030) and active anterior pelvic tilt (R^2=-0.664; p=0.026) indicating that in participants with the most restricted static flexibility demonstrated the largest changes active measures (Table 5.1). Changes in stride length also had a significant correlation with changes in hip extension (R^2=0.797; p=0.005) and pelvic tilt (R^2=0.774; p=0.007).

Table 5.2: Correlation matrix for key kinematic variables at 15km/h (Baseline measures = mean of weeks -4 and 0; change = difference between baseline and week 8 measures). Pearson's coefficients are presented in the non shaded area (*=significant correlation), significance values are presented in the shaded area.

	Static Flex	Static Flex Change	Stride Length	Stride Length Change	Active Hip Ext	Active Hip Ext Change	Pelvic Tilt	Pelvic Tilt Change
Static Flex		**-0.660***	-0.450	**-0.892***	0.227	**-0.646***	-0.181	**-0.664***
Static Flex Change	**0.026**		0.411	0.555	0.002	0.149	0.112	0.289
Stride Length	0.112	0.136		0.388	0.089	0.031	-0.226	0.477
Stride Length Change	**0.001**	0.61	0.151		0.000	**0.797***	-0.041	**0.774***
Active Hip Ext	0.279	0.498	0.410	0.500		-0.244	**-0.915***	0.400
Active Hip Ext Change	**0.030**	0.351	0.468	**0.005**	0.264		0.092	0.452
Pelvic Tilt	0.321	0.387	0.280	0.459	**<0.001**	0.407		-0.368
Pelvic Tilt Change	**0.026**	0.226	0.097	**0.007**	0.143	0.111	0.165	

5.5 **Discussion**

The aim of this study was to investigate the effect of a hip flexibility intervention programme on the running kinematics of triathletes. It was hypothesised that such an intervention programme would improve hip flexibility, which in turn would increase stride length, hip extension and thigh extension in triathletes and make their running technique more similar to that of pure runners.

The flexibility intervention programme implemented in this study was successful at increasing static ROM in both the IP and the RF, with increases in these measures of approximately 8° and 13° respectively. These improvements are comparable with the findings of Winters et al., (2004) who also found that the significant changes in their Thomas test measures occurred after 3 weeks and plateaued in the latter stages of their 6 week intervention, a finding replicated in the current study.

In comparison to the static measures, the kinematic measures showed no change over the course of the study with participants exhibiting running kinematics comparable to those of similar triathletes (Connick, 2009). Specifically, triathletes in the current study demonstrated restricted stride length of 2.89m, thigh extension of 66.39° and anterior pelvic tilt of 14.95° at 15km/h, comparing favourably with that of 2.88m, 68.49° and 15.85° previously presented by Connick, (2009).

There could be a number of reasons as to why the intervention was unsuccessful at making triathlete running technique more similar to that of runners, the most likely being the narrow focus upon hip flexor flexibility adopted in this study. Given that pelvic tilt and hip extension have been shown to be highly coordinated movements both in the current study and previous studies (Schache et al., 2000) it may have been more effective to attempt to anterior increase pelvic tilt as well as hip extension rather than concentrate on the latter in isolation. Correlation analyses carried out in this study also provide further support this as change in stride length from baseline to Week 8 were significantly correlated with increases in both hip extension and anterior pelvic tilt at all velocities. However, excess anterior pelvic tilt has previously been linked to increased lumbar lordosis and subsequent lower back pain (Schache et al., 2002) so a cautious approach was justified.

As in previous studies (Schache et al., 2000) there was no correlation between stride length and static hip extension shown in this study, providing further support to the notion that static soft tissue restraints are solely responsible for restricted hip extension in running. Correlation analyses did show however that participants with the least static hip extension at baseline demonstrated the greatest increase in static flexibility, stride length, hip extension and pelvic tilt following the intervention programme. Whilst the flexibility programme used in the current study may not be effective at increasing stride length within the general triathlete population, further research is warranted to investigate the use of such a programme in participants with severely restricted static hip extension.

Age of the participants and level of experience could also be a factor that prevented any significant changes in running kinematics. The participants tested in this study ranged in age from 18 to 44 years, with between 2 and 8 years experience in triathlon. Over this amount of time they are likely to have become accustomed to the restricted running technique they have adopted and that an 8 week programme is not long enough for them to adapt to be able to use the newly available ROM. Moreover, the lack of change in running gait could be that participants do not know how to apply their new ROM nor need to use it to perform at the velocities used in this study. Further research should be conducted as to the effect of using methods to instruct participants how to accommodate the acquired gains in flexibility.

Increased velocity has previously been shown, in runners, to require increased stride length, hip and thigh extension, and anterior pelvic tilt; results from this study and others (Connick, 2009) show that the same is true in triathletes. Such changes in these movements allow propulsive forces to be applied in a more efficient horizontal direction at minimal additional metabolic cost (Novacheck, 1998). The ability of participants in this study to increase these parameters as running velocities was increased indicates that, when the conditions necessitate, they can increase stride lengths. Furthermore, Schache et al., (2000) proposed that soft tissues that restrain movement during the test may only inhibit running technique at maximal velocity. It may be the case that at a velocity that requires maximal stride length, an increase in available hip flexor ROM could result in increased stride length; further support for instructing participants in future studies how to use the increased flexibility as, it appears they have sufficient ROM for increasing velocity but are not able to use it during running.

In conclusion, this study aimed to find the effect of a hip flexor flexibility programme on running performance in triathletes. Whilst the programme was effective at increasing static ROM of motion, these changes were not reflected during running performance. Thus, results suggest that the decreased stride length, hip extension and anterior pelvic tilt typically exhibited by triathletes are not solely due to tight hip flexors. Further research is required to investigate what other adaptations may be the cause of the altered running kinematics present in this group and how refining them affects performance.

.

Chapter 6: THE EFFECT OF RUNNING TECHNIQUE DRILLS AND HIP FLEXIBILTY TRAINING ON TRIATHLETE RUNNING KINEMATICS

6.1 Abstract

Restricted hip flexibility, brought about through cycling, is the proposed cause of differences in running technique between runners and triathletes. However, changes in static flexibility, through an 8-week hip flexor flexibility programme, do not translate into greater hip extension during running.

In order to examine the effects of a combined running technique drills and flexibility programme, 9 triathletes, undertook a 16 week training intervention. Between weeks 0 and 8 participants carried out a series of running drills aimed at improving pelvic position. Between weeks 8 and 16 these drills were then combined with a hip flexor flexibility programme. Every 4 weeks, static hip ROM and running kinematic data were collected at 13 and 15 km/h. Results show, that throughout the duration of the study, no significant changes in running kinematics occurred. The finding that an 8-week flexibility programme is effective at bringing about significant increases in static hip extension was replicated in this study. Likewise, these improvements did not translate to increased active hip extension during running.

It is concluded that changing running technique is not as simple as a structured technique and/ flexibility programme. The lack of change in technique brought about through drills does not mean that such programmes should not be used in training. However they do highlight that the specific drills used, in this specific population are not effective.

6.2 **Introduction**

Cycling is the proposed cause of long term adaptations to triathlon (Connick, 2009; Chapter 3); in comparison to pure runners, triathletes exhibit shorter relative strides and decreased hip ROM, thigh extension, hip flexion and anterior pelvic tilt in comparison to runners (Connick, 2009; Chapter 3). It has been postulated that these differences are a result of the large volumes of cycling training undertaken by triathletes (Gulbin and Gaffney, 1999; O'Toole, 1989) and the flexed position the hips and pelvis are maintained in throughout (Connick, 2009; Chapters 3,4 and 5 Furthermore, the extremely flexed, aerodynamic position adopted by cyclists and triathletes alike (Callaghan, 2005), appears to cause decreased hip extension flexibility which may account for reduced hip ROM and thigh extension capability during running (Chapter 3).

Hip flexor stretching programmes have been widely reported as being an effective intervention for increasing stride length in groups who are predisposed to reductions in stride length, such as the elderly (Christiansen, 2008; DiBendetto et al., 2005; Watt et al., 2009). Additionally, both static and active stretching has also been found to be effective at increasing extension (Winters et al., 2004). However, despite significantly increasing static hip extension capability, no significant changes were found in stride length, stride rate, active hip extension, thigh extension or anterior pelvic tilt when an 8-week hip extension programme was implemented in a triathlete cohort (Chapter 5). The authors proposed that the lack of change in active measures may have been as a result of the narrow focus on hip flexibility as a mechanism to change running technique.

In view of the multiple differences between the running technique of runners and triathletes, the narrow focus on increasing only hip extension seems a plausible reason for the limited effectiveness of a hip flexibility programme in modifying the running technique in triathletes. However, the narrow focus on hip extension throughout Chapter 5 is justified because of the increased injury risk associated with excessive anterior pelvic tilt. Given that triathletes have been shown to demonstrate less anterior pelvic tilt than healthy runners (with no previously reported lower back pain) (Connick, 2009), this may have been an overly cautious approach. Furthermore, anterior pelvic tilt and hip extension have also been shown to be highly coordinated movements in both runners (Schache et al., 2003; Franz et al., 2009) and triathletes (Connick, 2009; Chapter 3 and 4). Correlation analyses carried out in Chapter 5 also provide further support this as the small changes that did occur in stride length within a small number of participants were significantly correlated with increases in both hip extension and anterior pelvic tilt. Therefore, it may be necessary to modify both hip extension and pelvic tilt in triathletes in order to bring about running technique modifications.

Technique training drills are frequently advocated within running coaching literature (Bosch and Klomp, 2005). In modifiying technique, such drills are useful and necessary to teach athletes how to translate sensory information into coordination (eg. position of the joints and muscular stiffness). Being able to adequately process this information enables athletes to position their body more consistently and advantageously (Bosch and Klomp, 2005). Despite their seeming popularity, only a small number of empirical studies have investigated the use of such drills in training. Whilst these studies have addressed, in a variety of sports, the similarities between training drills and the movement patterns they are designed to promote (Wilson et al., 2009) and the injury reduction potential of such drills (Cameron et al., 2009) very limited data have been published on the modification of running technique through training drills. Such a gap in the literature seems particularly surprising, given the link between running technique alterations and running economy (Petray and Krahenbuhl, 1985; Dallam et al., 2005; Tseh et al., 2008). One of the few studies addressing the use of drills in running technique modification (Dallam et al., 2005) aimed to completely change the running technique of a group of triathletes. The findings of this study demonstrated that 12 weeks of training and tuition in the Pose method of running brought about significant decreases in stride length and vertical oscillation. Although this study provides useful information about running technique modification, it should be noted that these adaptations were brought about in response to a programme aimed at completely changing technique rather than one in which subtle joint specific changes were targeted. Furthermore, triathletes were tested in this study as they were anticipated to have a less developed running style than pure runners and not because the programme was designed to specifically address the running technique differences between triathletes and runners.

It was postulated in Chapter 5 that increased hip flexibility in isolation did not result in running technique changes because the triathletes in their study had become accustomed, over many years, to running with their restricted style. Using running drills to refine running technique within triathletes may enable them to incorporate the improved hip flexibility brought about as a result of a hip extension flexibility programme into their running.

Therefore the aim of this study is to assess the impact of a combined running technique and hip flexibility programme on the running kinematics of triathletes. It is hypothesised that improvement of pelvic kinematics through running drills, together with increased hip flexibility will result in triathletes displaying a running technique more similar to runners. This study will also seek to address some methodological limitations of the prior hip flexibility study by recruiting participants with similar triathlon experience, age and training regimes.

6.3 **Methods**

Participants

Ten healthy, injury free participants volunteered to take part in this study, 4 females and 6 males (age 21.6 ± 2.9 years (SD), height 1.68 ± 0.10m, weight ± 70.91 ± 10.85 kg). All participants were experienced triathletes with a mean of 3.6 ± 1.67 years experience of training and competing and had not previously trained exclusively as runners. In order to address the issues surrounding control of participant training regime previously raised (Chapter 5), all participants were recruited from the same club and were undertaking similar training regimes. The study was approved by the University ethics committee and all participants provided written informed prior to taking part.

A within-participant, repeated measures study approach was used. Participants visited the lab on 5 occasions and during each lab visit measures of static hip flexibility and running kinematics at 13 and 15km/h were performed (these procedures are presented in detail in Chapter 2). Each lab session was separated by 4 weeks. Between Weeks 0 and 8 participants carried out a running drills training programme, and between Weeks 8 and 16 the running drills programme was supplemented with an 8 week flexibility programme (Table 6.1). All data collection took place during the off-season phase of the participants' training cycle.

Running Drills Intervention Programme

Between Weeks 0 and 16, participants carried out a series of progressive running technique drills, the focus of which was the development of both postural and pelvic control and coordination. Specific drills included high knee lifts whist clearing hurdles, skipping with single ground contact and skipping with single ground contact and pauses (Bosch and Klomp, 2005). Throughout the sessions, emphasis was placed on minimizing both pelvic obliquity (ie. No leaning towards the stance leg) and posterior pelvic tilt and maintaining a stable core. Progression of drills was achieved through a combination of increased complexity of movement (e.g. performing hurdles drills backwards), increased speed of execution or by additional challenges to stability) e.g. hands on the head, elbows back). Participants were required to attend one coach-led drills session a week, during which an experienced triathlon coach prescribed and progressed exercises as required. Participants were free to perform their second drills session of the week at their own convenience. All drills sessions lasted 30 minutes.

Table 6.1: Study outline, following 8 weeks of technique training in isolation, this was combined with flexibility training.

Phase	Time	Intervention Volume (sessions/week)	Lab Procedures
Drills	Week 0	2 x drills	Static Hip ROM Running Kinematics
Drills	Week 4	2 x drills	Static Hip ROM Running Kinematics
	Week 8	2 x drills + 3 x Flex	Static Hip ROM Running Kinematics
Drills + Flexibility	Week 12	2 x drills + 3 x Flex	Static Hip ROM Running Kinematics
Drills + Flexibility	Week 16	2 x drills + 3 x Flex	Static Hip ROM Running Kinematics

Flexibility Intervention Programme

Between weeks 8 and 16 participants were also prescribed a bilateral hip flexibility programme, to carry out 3 times a week on non-consecutive days; details of the specific exercises can be seen in Figure 6.1. All stretches were maintained for 30 seconds on each leg (Winters et al., 2004) and repeated 5 times. The initial flexibility session took place in the laboratory with instruction, demonstration, feedback and monitoring from the experimenters, ensuring that participants were aware of the correct technique for each stretch. Throughout the programme an experimenter was present for one flexibility session per week, at the convenience of the participant. This enabled the experimenters to correct exercise technique if necessary, maintain participant motivation and advise the participants when to progress through the exercise programme.

A multifaceted approach was taken to monitor participants' adherence to both the drills and flexibility programme. All participants were provided with a training manual with details of the both the drills and flexibility exercises and a training diary to record when they performed the drills and stretches and any comments they had about the session. Participants were also provided with a url to videos of their running drills.

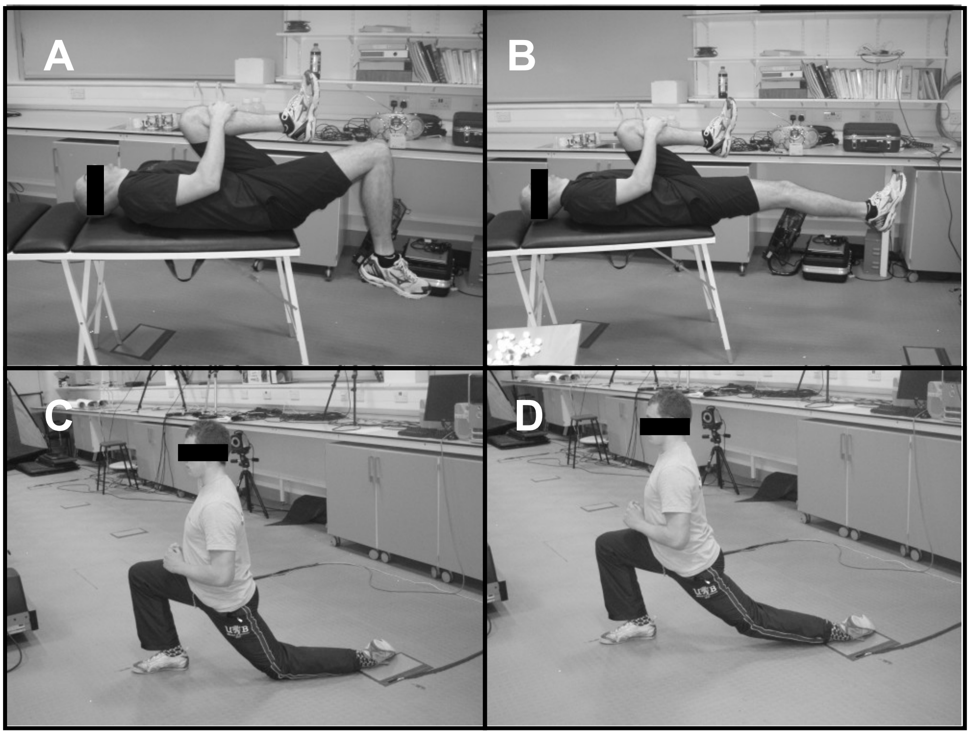

Figure 6.1: Stretches performed throughout the flexibility intervention period. Initially the participants were instructed to perform exercises A, B and C. When the experimenters deemed the participants were proficient at the initial exercises (based on their ability to perform the exercises and the amount of stretch they reported feeling during the exercise) their programme was advanced by using progressions of exercise C, either by straightening the knee of the stretched leg (D) and incorporating holding the arms above the head or reaching across to the opposite side of the body to increase the stretch felt across the hip.

Statistical Analysis

Two-way repeated measures ANOVAs were used for establishing the effect of time and velocity on the static hip ROM measures and kinematic measures. Prior to these tests, Maulchy's test of spherecity was conducted. In instances where a significant lack of homogeneity of variance was indicated, Greenhouse-Geisser corrections were utilised. An LSD post hoc test was used to ascertain between which times the differences occurred. The significance level was set at $\alpha=0.05$.

6.4 **Results**

Of the ten participants recruited, 9 completed the full study as 1 male participant withdrew from the study due to shin splints (the data of the 9 remaining participants are presented hereafter). Overall adherence to the intervention programmes was good with all participants completing, both supervised and unsupervised, at least 87.5% of the running drills sessions and 91.6% of the flexibility sessions. Furthermore 50% of the drills sessions and 33.3% of the flexibility sessions were supervised.

Across the 16 weeks intervention period, hip extension flexibility was the only variable to change, with large increases of 9.5° and 9.4° seen in the rectus femoris and iliopsoas respectively (Figure 6.2).

No changes in stride length, stride rate, hip extension, thigh extension or pelvic tilt were observed either during the running drills intervention between Weeks 0 and 8 or during the combined intervention of drills and flexibility between Weeks 8 and 16.

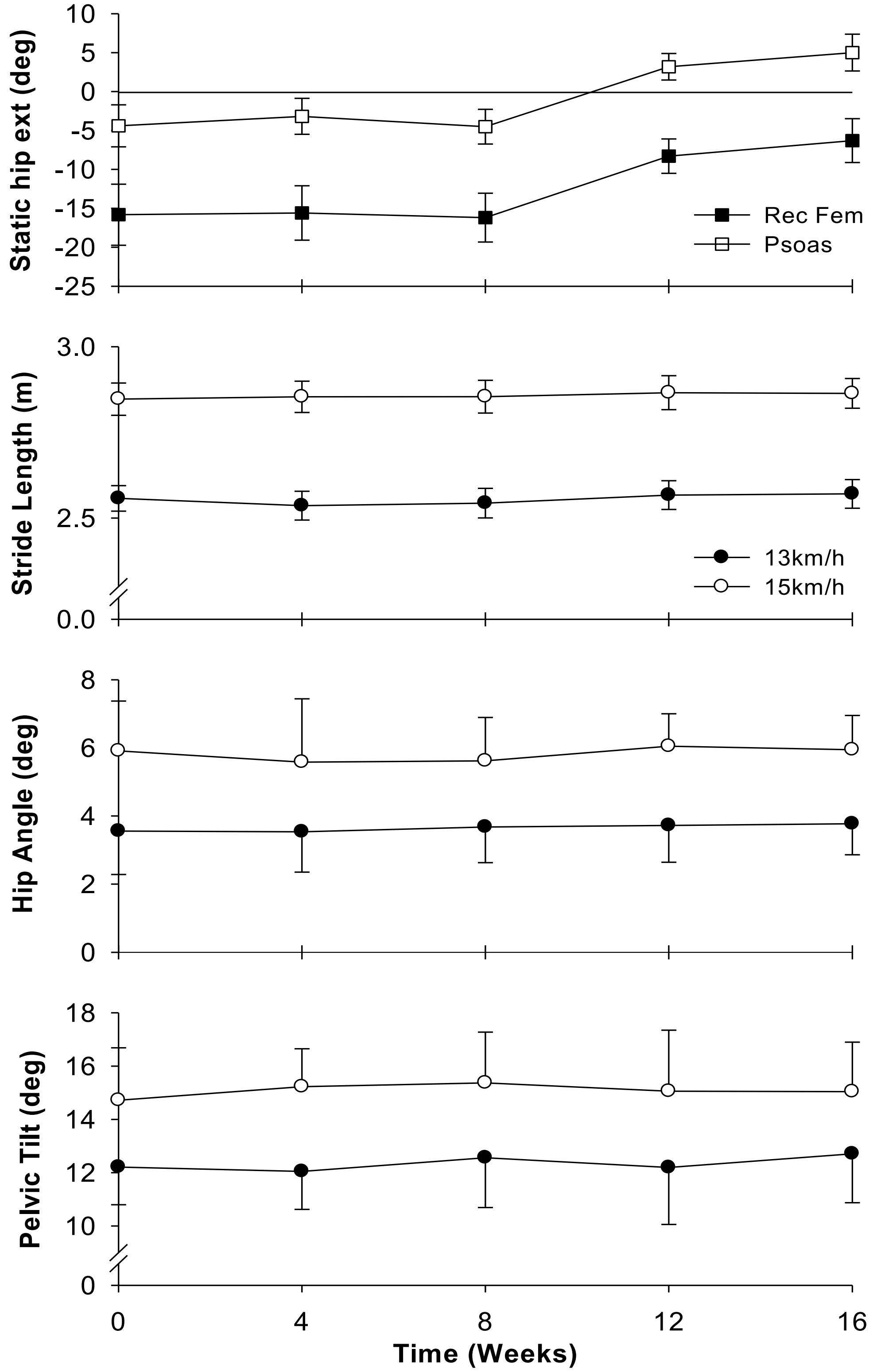

Figure 6.2: The effect of time and velocity on A) static hip flexibility (±SEM), B) stride length (±SEM) C) hip extension (±SEM) and D) pelvic tilt (±SEM) over the 16 week study.

There was a significant main effect of time on hip extension flexibility both in the rectus femoris measure [F(1.929, 15.433)=11.889 p<0.001, η^2=0.598] and the iliopsoas measure [F(1.933, 15.461)=13.738, p<0.001, η^2=0.632]. Post hoc analysis showed that these changes occurred following the commencement of the flexibility intervention between weeks 8 and 16. As such there were significant increases in both measures between weeks 0 and 12 (RF p=0.025; IP p=0.013), weeks 0 and 16 (RF p=0.002; IP p<0.001), weeks 4 and 12 (RF p=0.011; IP p=0.021), weeks 4 and 16 (RF p=0.003; IP p=0.001), weeks 8 and 12 (RF p=0.002; IP p=0.006) and weeks 8 and 16 (RF p=0.002; IP p=0.002).

Stride parameter and joint kinematic measures remained relatively constant throughout the study as there was no main effect of time on these measures, indicating that neither the running drills in isolation or when combined with the flexibility programme had any effect on stride length [F(1.699, 13.592)=0.91, p=0.412, η^2=0.102]; stride rate [F(4,32)=0.533, p=0.73 η^2=0.013]; hip extension [F(4, 32)=0.263, p=0.90 η^2=0.032]; thigh extension [F(4, 32)=3.695, p=0.014 η^2=0.316] or anterior pelvic tilt [F(4, 32)=0.103, p=0.757 η^2=0.013] (Figure 6.2). Means and standard deviation of additional kinematic variables can be found in Appendix D.

6.5 **Discussion**

The aim of this study was to assess the impact of a combined running technique and hip flexibility programme on the running kinematics of triathletes. It was hypothesised that improvement of pelvic kinematics through running drills, together with increased hip flexibility would result in triathletes displaying a running technique more similar to runners.

Baseline running kinematic measures in the current study compare favourably with those previously recorded within a triathlete population (Connick, 2009; Chapter 3), indicating that participants in this study did display a running technique that had been influenced by long term adaptations to triathlon. Baseline hip flexibility measures of -4° and -16° in the iliopsoas and rectus femoris respectively, also compared favourably to previously documented measures of -4° and -16° in triathletes (Chapters 3 and 5). Furthermore, these measures were far less than those previously reported in pure runners (Schache et al., 2003), indicating the restrictive effect triathlon training has on the hip musculature (Chapter 3).

In a previous study designed to enable triathletes to overcome restricted hip flexor flexibility, an 8 week flexibility programme was administered in isolation (Chapter 5). In spite of a significant increase in static hip flexibility measures, the intervention was not successful at increasing active hip extension measures. The authors postulated this was due the participants' inability to use the newly available flexibility during running as they were accustomed to the restricted running technique they had adopted. In order to overcome this problem, a running drills intervention was implemented in the current study to improve pelvic kinematics. However, no significant changes in running technique were seen either between weeks 0 and 8 as a result of the running drills programme in isolation or between weeks 8 and 16 as a result of the combined drills and flexibility intervention. This seems particularly surprising given that the drills programme was formulated by an experienced triathlon coach and such drills are frequently recommended within the coaching literature (Bosch and Klomp, 2005).

A possible explanation for the lack of effectiveness of the drills in the current study may be the volume prescribed to the participants. However, this seems unlikely as it has been previously reported that 1 hour of technique instruction per week over a 12 week period, was sufficient to cause significant changes in running kinematics (Dallam et al., 2005). Yet, despite the greater volume of training drills (16 weeks, 2 hours per week), no such changes occurred in the current study. The different focus of the drills used in the current study compared to that of Dallam et al., (2005), may provide a plausible explanation for the differing intervention outcomes. The aim of the drills used by Dallam et al., (2005) was the global alteration of running technique, whereas the current study aimed to bring about subtle technique changes in a specific body segment. Perhaps of more importance is that the broad approach adopted by Dallam et al., (2005), enabled the authors to instruct participants to actively incorporate their newly developed movement patterns in to their normal running training sessions. In contrast and in light of the more subtle adaptations targeted, no such instruction was given to the participants of the current study. Additionally, the subtly of the desired changes in the current study, in comparison to those implemented by Dallam et al., (2005) may also have affected the likelihood of statistically significant changes in technique being displayed. However, the disparity between findings of the current study and those of Dallam et al., (2005) highlight the need for more research as to the effectiveness of commonly used running technique drills. Further studies should aim to address issues such as the efficacy of varying types of drills (global vs specific), the volume of drills necessary to bring about significant changes in technique and the type of instruction amongst others.

Given that the running drills intervention programme failed to bring about the desired changes in running technique, it seems that both flexibility and flexibility in combination with the specific drills used in the current study can be discounted as methods to bring about running technique modifications in triathletes. These findings however do not mean that technique drills should not be used in training. However they do highlight that the specific drills used, did not work in this specific population.

In terms of flexibility intervention, the current study confirms the findings presented in Chapter 5, that an 8-week flexibility intervention programme is effective at bringing about significant increases static hip extension ROM in triathletes but that this does not result in increased active hip extension during running. To address methodological issues raised in the aforementioned study, participants in the current study were from a much narrower age bracket, had less triathlon experience (therefore had spent less time running with the adapted style of triathletes) and all undertake similar training regimes. Given that the findings from Chapter 5 are replicated in the current study, the proposed link between the lack of change in running technique and age and experience of participants can be discounted.

The participants in the current study also differ from those in Chapter 5 in they include both males and females. Chapter 4 of this thesis indicates that in spite of gender-specific technique differences in the component parts of triathlon, the same long term adaptations to triathlon are seen within both females and males. In view of this finding and given that the intervention programmes were designed to overcome such adaptations participants of both genders were recruited for the current study.

Although the small number of participants in this study means statistical analysis of any gender specific effects is likely to be not valid, visual inspection of the data indicates that there were no gender differences in the responses to the intervention programmes.

In conclusion, this study aimed to assess the impact of a combined running technique and hip flexibility programme on the running kinematics of triathletes. However, the running technique drills failed to bring about any modifications in running kinematics consequently it is yet is be confirmed whether refinement of running technique together with increased hip flexibility can bring about positive changes in the running technique of triathletes. Further research is required to develop a successful protocol by which to modify running technique. This study also highlights the need for research in to the efficacy of common training drills used for developing running technique, as in spite of anecdotal evidence to the contrary; the drills used in the current study appear to have little impact on running kinematics.

As the interventions implemented in this study failed to bring about adaptation in triathlete running technique, the larger scale question of whether modifying running technique of triathletes to be more representative of runners can bring about performance improvements in triathletes is yet to be answered.

Chapter 7: A LONGITUDINAL CASE STUDY OF AN ELITE FEMALE TRIATHLETE

7.1 Abstract

Running technique is susceptible to change in response to factors such as fatigue and the multidisciplinary training typically undertaken by triathletes. Furthermore, both of these factors are liable to change throughout training cycles. A longitudinal case study of an elite female triathlete, in relation to her training regime, provides a novel insight in to the biomechanical factors affecting performance.

Throughout an 18-month period, encapsulating 2 pre-seasons, 2 race seasons and 1 off season, running kinematic data were collected at participants' anaerobic threshold pace (17km/h), lactate threshold pace (15km/h) and aerobic training pace (13km/h). Results demonstrate that, although stride length remained relatively constant throughout the duration of the study, during periods of high training volumes, running kinematics were prone to changes. Specifically, contact time and vertical displacement increased, whilst contact knee angle and stance knee flexion both decreased during the race season. However, these modifications were reversed during the Off-season.

It is concluded that changes to running kinematics took place in response to training demands throughout the season and the associated fatigue levels. In light of the novel approach to this research area, methodological issues encountered throughout the study are also discussed.

7.2 **Introduction**

Optimum endurance performance is reliant upon the translation of cardiorespiratory factors into well controlled, efficient movement and muscle recruitment patterns (Chapman et al., 2009). Accordingly, the biomechanics of endurance running has received much attention within the scientific literature. The vast majority of studies conducted within this area can be subdivided into either those that provide descriptions of specific variables associated to running performance (Williams and Cavanagh, 1987; Novacheck, 1998) or those in which interventions are administered (Dallam et al., 2005;Tseh et al., 2008). Studies conducted within the biomechanics literature have demonstrated that, on the whole, running technique remains relatively constant, particularly within experienced performers (Millet et al., 2000), yet in response to conditions such as fatigue (Nicol et al., 1991; Derrick et al., 2002; Mizrahi et al., 2000; Dierks et al., 2010), it is prone to change.

Of the three disciplines that combine to form triathlon (swimming, cycling and running), running has been highlighted as the greatest predictor to overall race outcome (Millet and Bentley, 2004; Vleck et al., 2008). Biomechanical studies conducted in triathlon running can also be divided into those that provide a description of running technique and intervention studies. Typically, studies that are of a descriptive nature within triathlon running have focused on the immediate effects of cycling on subsequent running (Millet et al., 2001), the effect of bicycle frame design and cycling position on running and the running kinematics of triathletes compared to pure runners (Connick, 2009; Chapters 3 and 4). Longer term, intervention studies have examined, amongst others, programmes designed to overcome the long term running adaptations to triathlon (Chapters 5 and 6) and the effect of specific training modalities on running kinematics (Palazzetti et al., 2005). Such studies provide a useful insight into the factors affecting running performance and can demonstrate the effect of specific training programmes on key performance factors but are not without their drawbacks.

Biomechanical studies of both elite runners and triathletes have typically been designed to examine the difference between elite performers and sub-elite performers (Cavanagh et al., 1977; Millet et al., 2000). Whilst this is of interest to the scientific community and the sub-elite performer, it provides very little in the way of performance enhancement for the elite athlete. As elite athletes are unlikely to allow their training regime to be tampered with for the sake of scientific research (Midgley, et al., 2007), studies of training interventions also tend look at the way in which the average athlete responds to a specific programme, rather than the way in which the elite do (Kinugasa et al., 2004). Therefore, due to methodological constraints these studies have strong limitations.

Frequently findings reported within studies such as the aforementioned ones are based upon sample means and may subsequently mask important findings for a given individual (Kinugasa et al., 2004). Within performance physiology, the theory of individualisation suggests that even when presented with identical training regimes individual athletes will respond differently to these, over differing time frames (Norris and Smith, 2002 cited by Smith, 2003). Although important and useful findings for the ‘average’ athlete may be unearthed in cross-sectional studies, applied performance research requires a far more individual approach for the elite athlete (Kinugasa et al., 2004). Studies on elite performers are also limited by the very essence of elite, i.e. the very small number of athletes that achieve elite level. Consequently studies attempt to analyse very small, often not very homogeneous, groups. Furthermore, the statistical treatment of very small number of participants leaves some results open to criticisms (Backman and Harris, 1999; Kinugasa et al., 2004).

Case studies provide a method by which the performance of one or a small number participants can be monitored as a dependant variable throughout a given time period (Kinugasa et al., 2004). Furthermore, in specialised groups where participant recruitment is severely restricted (e.g. the elite), a series of case studies enables informative research without the restriction of participant numbers having to be met to enable sound statistical interpretation of findings (Backman and Harris, 1999).

In designing training programmes, coaches are faced with the problem of developing a programme that maximises the performance potential of a given athlete for a specific date (or a series of dates) whilst minimising the risk of fatigue, injuries and over-training (Morton, 1997). Traditionally, the training year is divided into preparatory, competitive and transition or recovery phases (Smith 2003) and given the known links between fatigue and running technique, the changing demands of training may influence an athletes running performance throughout the year. Coupled with the varied training typically undertaken by triathletes (Gulbin and Gaffney, 1999; O'Toole, 1989), a record of running technique throughout the season could provide a useful insight of the effects of triathlon training.

Within various forms of running, only a limited number of studies have addressed the quantification of longitudinal responses to training. In one such study carried out in the physiology field (Jones, 1988), a five year, longitudinal case study of an Olympic 3000m runner was performed. Whilst this study provides an insight as to the physiological adaptations of an elite performer over a long period of time, interpretation of the findings is restricted by the lack of empirical data regarding training. Conversely, in a biomechanical study addressing the relationship of stride rate and velocity in an elite sprinter (Bezodis et al., 2008) publication of training data allowed a clear insight as to the concurrent changes in velocity and stride rate that occurred due to the training plan. These studies (or rather lack of) not only emphasise the limited volume of elite case studies available in the literature but also highlight the importance of a tight collaboration between the scientist and, the coach and elite athlete. Without such relationship the information about training regimes may be restricted and subsequently the practical significance of the research hindered.

Given the individual characteristics of an elite sports person, the intensity with which the elite train and the previously reported propensity for running technique to change over time and as a result of external factors; this study aims to examine the running technique of elite triathletes in relation to their training. A series of 18-month longitudinal case studies, will provide a novel insight in to the biomechanical factors affecting their performance.

7.3 **Methods**

Three female participants volunteered to take part in this study. All participants trained were highly experienced triathletes and competed in triathlon internationally, had at least 2 years experience at this and had not previously trained exclusively as runners prior to starting triathlon. The study was approved by the University ethics committee and all participants provided written informed consent.

Of the 3 participants recruited only 2 completed the full study, with 1 withdrawing early in the study due to time commitment issues. Of the 2 that completed the whole 18 months, 1 participant suffered a recurring injury and subsequently missed a large number of data collection sessions. Moreover, this participant’s data were potentially influenced by the injury; a variable not considered to fit the remit of this study, therefore the data of one participant (age 18 years, height 166.3cm and weight 62.5kg) is presented hereafter. It is of note that this participant changed coach following the first data collection.

Monthly data collections were initially planned for the duration of the study, however given travel commitments, a total of 9 data collection sessions took place throughout an 18-month period that incorporated 2 pre-season phases, 1.5 competition seasons and 1 off-season (Figure 7.1). Throughout the duration of the study, the participant was injury free.

Data collection sessions commenced with a 5 minute warm up run at 10km/h on an h/p Cosmos treadmill. For motion capture, participants carried out 3 x 2-minute bouts of running on the same treadmill, at 3 different velocities, chosen after consultation with the triathletes' coach. The velocities represented anaerobic threshold pace (17km/h), lactate threshold pace (15km/h) and aerobic training pace (13km/h) which had been determined by the coach using the appropriate physiological methods (motion capture and data processing are presented in detail in Chapter 2).

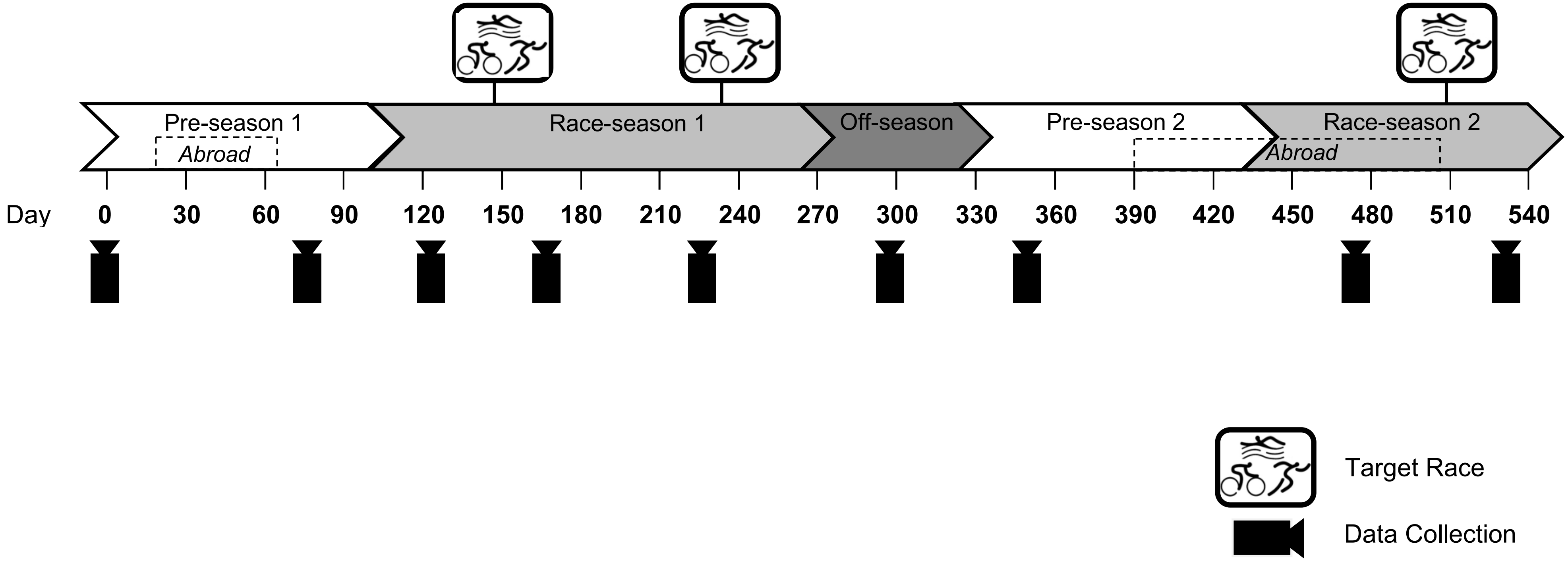

Figure 7.1: Timeline of study duration including data collections and focus races.

7.4 **Results**

Complete timescale details of the duration of the study are presented in Figure 7.1. Day 0, taken during the pre-session phase, is the first data collection. This is the only test session during the time the participant was working with her original coach, she then changed coach and remained with this coach. Two prolonged intense pre-season training blocks abroad, limited the data collections during this phase. Data collections continued through the competition, off-season (including a session following a 2 week complete rest period) and the following pre and competition seasons. Key running stride parameters throughout the testing period are presented in Figures 7.2, 7.3, 7.4 and 7.5.

Across the 3 velocities tested, stride length had a mean range of 0.04m, ranging from 2.42-2.46m at 13km/h, 2.74-2.77m at 15km/h and 3.98-4.02m at 17km/h. For ease of comparison with previously published data, in Figure 7.2, stride length presented relative to leg length. Stride duration fluctuated between 0.67 and 0.68 seconds at 13km/h, 0.64 and 0.65 seconds at 15km/h and 0.63 and 0.64 seconds at 17km/h. Contact time ranged from 41% of the gait cycle on Day 73 to 46% on Day 221 and in contrast to stride length and duration was unaffected by velocity. Vertical displacement varied by 0.02m across the course of the study, and was also unaffected by velocity. Measures ranged from 0.11-0.13, with the peak occurring at Day 221 (towards the end of Race-season 1), and minimum at Day 339 (early Pre-season 2).

Figure 7.3 shows the contact position of the foot relative to the hip at contact and sagittal plane angles of the knee at foot contact. Contact position had a peak range of 0.04m across the velocities tested and a range of 0.06m over the duration of the study. Peak horizontal distance between the foot and hip occurred during the Off-season and was 0.31m at 13 and 15km/h 0.34m at 17km/h, minimum measures of 0.24m, 0.25m and 0.27m respectively, occurred during Pre-season 1.

Contact knee flexion steadily decreased by 3° at 13 and 15km/h between Day 0 and Day 221 (end of Race-season 1) and by 7° at 17km/h. Between Race-season 1 and the Off-season, contact knee angle increased by 8° at 13 and 15km/r and 11° at 17km/h. The steady decrease seen during the first Pre and Race-seasons and rises again during the second repetition of these phases (Day 339 to 535).

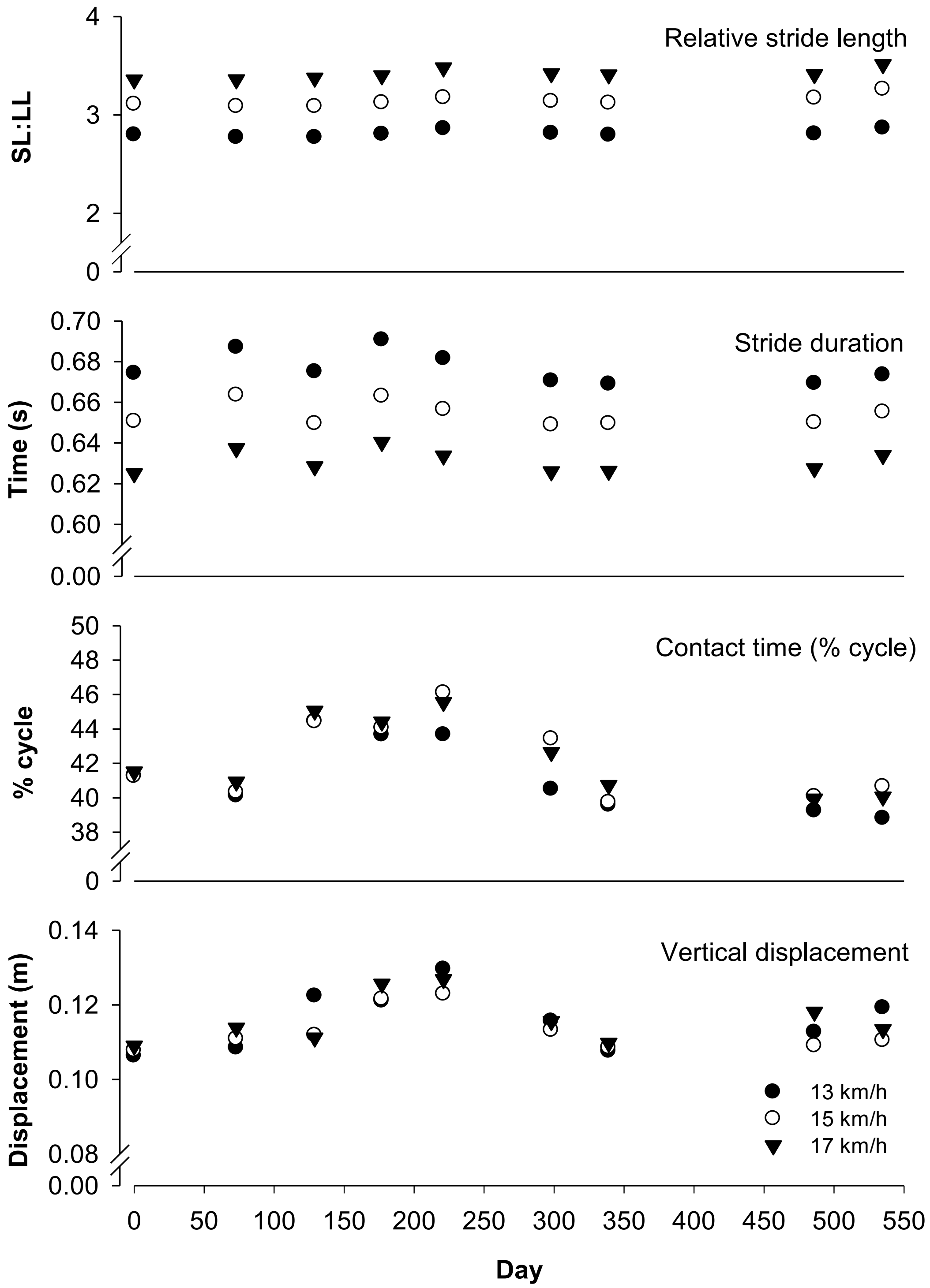

Figure 7.2: Chronological representation of key stride parameters A) relative stride length, B) peak vertical displacement, C) contact time and D) stride duration.

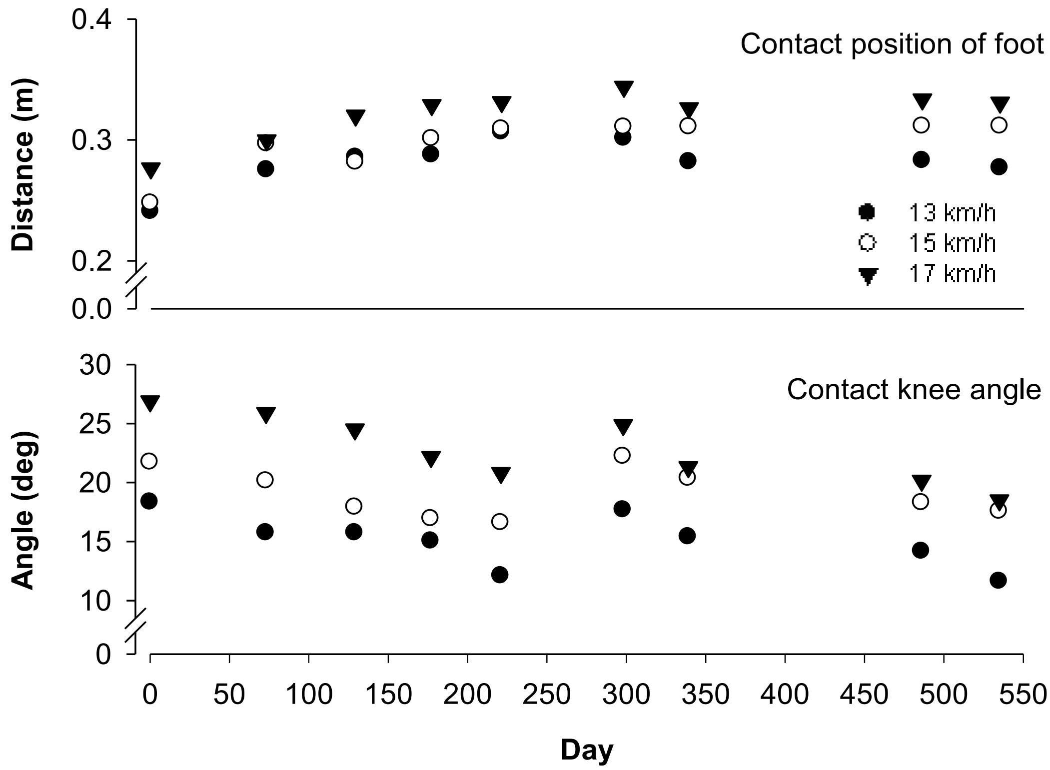

Figure 7.3: Chronological representation of key variables at foot contact: foot position relative to hip and knee angle at initial contact.

Figure 7.4 shows knee flexion during the loading response of the stance phase. Between Days 0 and 221these measures ranged between 40° and 46° at 13km/h, 41° and 46° at 15km/h and 42 and 47° at 17km/h. Between Days 221 and 298 (Off and early Pre-season2) these measures increased by 7°. By Day 486 peak stance knee flexion increased to 46° for all velocities and started to decrease again by day 535.

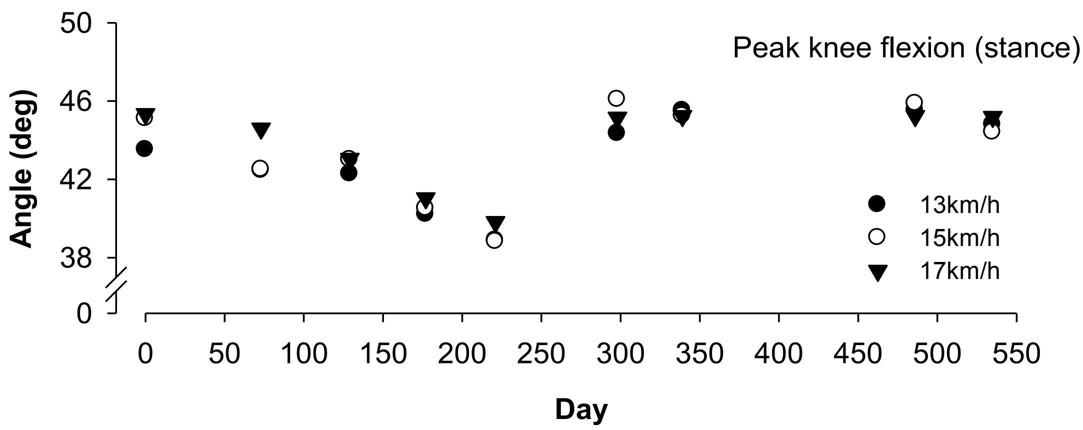

Figure 7.4: Chronological representation of peak knee flexion during stance.

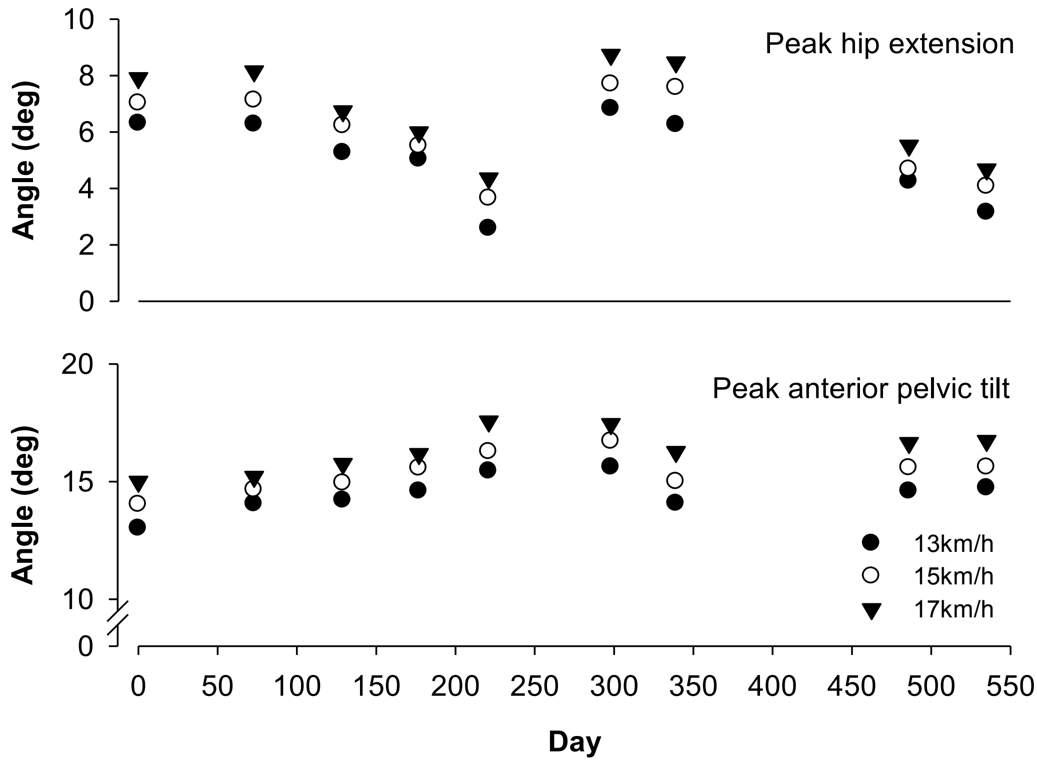

Figure 7.5: Chronological representation of peak hip extension and peak anterior pelvic tilt.

Of the peak kinematic measures examined previously within this thesis mean hip extension range of 4.2° across the 3 velocities sowed the greatest change, ranging from 2.6-6.8° at 13km/h, 3.6-7.7° at 15km/h and 8.7-4.4° at 17km/h (Figure 7.5).

Minimum hip extension occurred on Day 221 for all velocities and peaked during the off-season (Day 298).

Across all velocities, the mean range of anterior pelvic tilt was 2.6°, ranging from 13.0-15.6° at 13km/h, 14.0-16.7° at 15km/h and 15.0-17.6° at 17km/h.

7.5 **Discussion**

The aim of this study was to investigate the changes of running technique in 3 elite participants throughout an 18-month period. However, due to personal problems and injury, only one participant completed the study. Therefore this is a case study of a single world class triathlete. Kinematic data presented in Figures 7.2, 7.3, 7.4 and 7.5 show that, despite the relatively constant stride length throughout the 18 month period, changes to running kinematics take place in response to training demands throughout the season. Exploration of these findings will now be presented along with additional discussion regarding some of the methodological issues encountered throughout this novel research.

In comparison to the female sub-elite triathletes previously studied in Chapter 4, the current elite participant demonstrated a greater stride length relative to leg length than her sub-elite counterparts (Elite 2.81 at 13km/h and 3.14 at 15km/h; Sub-elite 2.75 at 13km/h and 3.05 at 15km/h). Whilst this is contradictory to previous work that has found that elite runners demonstrate shorter relative strides than lesser trained runners (Cavanagh et al., 1977), it has been documented that elite triathletes show smaller scale running modifications immediately proceeding cycling than sub-elites (Millet et al., 2000). It could therefore be the case that the running style of the participant in the current study has been affect ted less by long term modifications to the multi-disciplinary nature of triathlon than those sub-elite females who participated in Chapter 4. However, given that the participant's stride length relative to leg length was shorter than the runners studied in the same chapter (2.88 at 13km/h and 3.20 at 15km/h) it appears that some long-term adaptations have taken place. Moreover, other variables (peak thigh extension and anterior pelvic tilt) are of magnitudes akin to previously presented long-term adaptations to triathlon in both females (Chapter 4) and males (Connick, 2009).

Details of the participant's training plan throughout the study duration give an insight as to why changes in running kinematics may have occurred. Although it would be interesting to show these data, it cannot be presented for two reasons. Firstly, prior to commencement of the study it was agreed with the athlete and coach(es) that details which could potentially provide an advantage to her competitors would not be published. Secondly, some details would allow easy identification of the participant and this was not allowed in the ethics approval. Therefore, within these constraints inherent to case studies of the elite, only rough indications of the training regime the participant undertook throughout the duration of the study. Following the initial data collection on Day 0 the participant started a period of intense pre-season training, it was during this period that the participant's coach changed. Following the change of coach the focus of training was to build up the overall volume and intensity of the training. On return from pre-season training, the newly increased volume and intensity of training continued; additional attention was paid to increasing performance in the running discipline through cardio-vascular improvement rather than technical changes.

A typical training week during Race-season 1 comprised of approximately 22km swimming, 5 hours cycling, 7 hours running and 1 rest day. This typical training week continued most weeks throughout Race-season 1 (Day 115-280). Throughout this phase many variables: vertical displacement, contact time and contact foot position can be seen to gradually increase, whilst knee flexion at contact and during stance decrease. Contrary to what may be expected, many of the technique adaptations that took place in response to the increased demand of training during this period, have previously been found to related to factors known to adversely affect running economy.

Improved running economy has previously been reported to be related to a variety of kinematic variables including, but not limited to, reduced vertical oscillation (Cavanagh et al., 1997), reduced support time (Paavolainen et al., 1999) and increased knee flexion during support (Williams and Cavanagh, 1987). As the year progressed, the changes of running kinematics of the participant in the current study appear to change towards a less economical state. One factor that has been reported to cause such changes is fatigue. Be it at the end of a marathon (Nicol et al., 1991), following an exhaustive lab-based run (Derrick et al., 2002; Mizrahi et al., 2000) or following a “typical” training run (Dierks et al., 2010) it has been widely reported that fatigue has a detrimental effect upon running kinematics. Following a 30min run at above aerobic threshold pace, Mizarahi et al., (2000) showed that runners typically decrease stride frequency (at a set velocity this is accompanied by increased stride length) and increase vertical excursion of the hip. Potentially given the volume of training being undertaken by the athlete in the current study and given that increased substantially with the change of coach, the adaptations that she demonstrated throughout the season may be related to the additive effects of fatigue. This may be particularly pertinent during “Big Blocks” of training that were undertaken prior to focus races throughout the season (Day 159 and Day 242). However, the findings of Mizarahi et al., (2000) are based upon the immediate effects of an exhaustive run, not a condition that the participant visited the lab after. At the other end of the fatigue spectrum, Dierks et al., (2010) examined the effects of a “typical” training run and found that significant but small adaptations took place at the foot ground interaction site. They concluded that whilst only small changes occurred due to the training used in their study, larger changes in foot mechanics related to greater fatigue could cause degradation to running form by increasing joint motion, altering foot placement relative to COM and plantar loading. This could be particular pertinent to the participant in the current study who is likely to perform far greater volumes of training than that used by Dierks et al., (2010), again particularly during big blocks of training prior to important races.

Furthermore stride length (and subsequently stride rate given the matched velocities used for each test session) in this study remained constant throughout the course of the study apart from a notable peak on Day 221, adding further support to the proposed link between the effect of fatigue during the aforementioned “Big Block” of training and changes in running kinematics.

The effects of cycling on running have also been examined throughout the literature, with cycling immediately prior to running shown to cause biomechanical changes to stride frequency, trunk gradient and knee angle (Bernard et al., 2003; Gottschall and Palmer, 2000; Hausswirth et al., 1997; Millet and Bentley, 2004; Vleck et al., 2006).

Long-term adaptations have also been shown to exist, both in this thesis (Chapters 3, 4 and 5) and by Connick (2009). In agreement with this work and with that of Schache et al (1999), peak hip extension and anterior pelvic show an inverse relationship throughout the course of this study, with the former decreasing as the latter increases. Given the proposed link between cycling and alterations to the hip musculature (Connick, 2009) it is feasible that the trend of decreasing thigh extension and increasing anterior pelvic tilt throughout Pre and Race-seasons 1 are in response to the increased cycling volume undertaken when the change of coach occurred.

The Off-season brought about a dramatic reduction in training volume, and included a 2 week complete rest period immediately prior to the data collection on Day 298. During the Off-season the changes that occurred during the previous phases of the year are reversed with vertical displacement, contact time and contact foot position showing decreases between the end of the Race-season and the start of the Off-season along with relative stride length. Conversely, knee flexion at contact and during stance can be seen to increase during this time.

Training in Pre- and Race-seasons 2 was focused mainly on continuing with the same level running whilst improving performances in the other disciplines. As such, a typical training week during this period consisted of 29km swimming, 8.5 hours cycling and 7 hours running. Following the changes in kinematic data during the Off-season, the same trends of increased vertical displacement, contact time, contact foot position and peak hip extension alongside decreased knee flexion at contact and during stance and anterior pelvic tilt appear to start during Pre-season 2 and

Race-season 2, seemingly in response to increased training volume as discussed in the same periods in the first pre and race-seasons.

Pertinently, irrespective of stage of season, many of the kinematic changes in running technique throughout the season were found to occur to similar degrees in all velocities tested. One possible explanation is that the participant's training modified some characteristics of the internal models she used to control her running technique (e.g. Kawato, 1999). If this is the case, a change of one characteristic, possibly due to training at a given speed, would be reutilised at a different intensity.

Given the similarities between velocities and the commitment levels required of the participant to visit the lab on repeated occasions throughout the duration, future studies may consider only testing one velocity. This however, poses the question as to which velocity to test. The velocities in this study were chosen as a result of consultation with the participant's coach and were velocities suggested replicate physiological markers for the participant. The fastest velocity (17km/h) was suggested as it was a target velocity for the participant in order to achieve her target time in the run phase of the triathlon. Potentially this therefore is of more interest for the coach and athlete and the most pertinent regarding the effect of her specific training and race regime. However at times of fatigue (post race), recovery (off season) or preparation (pre-race taper) this may not be a velocity that the participant is able to and/or willing to perform at. Conversely the slowest velocity tested (13km/h) may be of little importance to the coach and athlete as it represents the speed of an easy run, as such has no importance to the coach regarding race performance. However, given that changes in technique occurred at all velocities tested, using the slowest velocity during scientific testing may minimise the additional load such testing places on the participant. This study presents the findings of 1 participant, whilst similar kinematic changes occur at each velocity for this participant, this may not be the case for everyone. Future studies of similar design and/or duration may consider using a velocity considered ‘achievable’ irrespective of training intensity/volume and a target velocity, if not for the duration, then at least at the beginning of the study to initially investigate whether the velocity similarities found in this study are replicated.

Another point of note related to the velocities used in the current study is that the kinematics adaptations that took place, seemingly due to training volume, may impact the velocity at which the participant would have chosen to perform.

Whist this study provides an in depth account of the running kinematic profile of a world-class female triathlete throughout an 18 month period, interpretation of its results must be made with the limitations of the study in mind. One of the key limitations of this study is the frequency at which data collections occurred. Ideally studies of this nature would have regular data collections, spread equally throughout the season, encompassing as many different parts of the years as possible. It was originally aimed that data collections would occur on a monthly basis but such are the training and travelling demands of an elite performer that this was impossible. The performer spent long periods of time out of the country training during the pre-seasons and racing. Conclusions of running technique changes in response to training made in this study also negate the smaller training cycles that are incorporated into the bigger divisions of off, pre and race seasons, for example tapering and rest in race preparation and recovery from races. Examination of these phases in future studies could reveal interesting findings in terms of running kinematics in both the lead up and recovery from racing.

It is clear from this study that data collection would have been easier with local sub-elite triathletes and a more regular sampling would help to clarify some remaining questions. It is therefore recommended that future studies investigate triathletes of various levels with various levels of constraints to build case by case a more complete picture of the long and short term effects of training.

Although not the case in this study, in some cases elite athletes may be unwilling to provide you with exact details of their schedule for confidentiality reasons. More pertinent to this study is that whilst the athlete and coach may be happy for the experimenter to have access to their training records, presentation of such information must be sensitive to the confidential nature of this information and subsequently may not allow the reader to gain the complete picture.

In conclusion, this study provides an in depth analysis of the running technique of an elite female triathlete through 18 months of her training schedule. In the participant studied, kinematic changes appear to occur due to changes in training demands and the associated fatigue. The proposed relationship between long term running adaptations to cycling in triathletes are noticeable, even in this world class athlete.

Chapter 8: GENERAL DISCUSSION

8.1 **Overview**

Triathlon comprises of three disciplines: swimming, cycling and running. Of the three disciplines, running performance has been found to be most strongly related to overall finishing time (Millet and Bentley, 2004; Vleck et al., 2008). Despite the vastly different movement patterns associated with each discipline, the importance of the running phase and, in relation to the endurance nature of triathlon, the substantial volumes of training undertaken by triathletes, only a very limited number of studies have addressed the long term effect of such multidisciplinary training on the running technique of triathletes (Chapman et al., 2008; Connick, 2009; Bonacci et al., 2010b). The thesis therefore set out to further explore these chronic adaptations and to apply this theoretical understanding to design and implement intervention programmes to modify the running technique used by triathletes and to assess the running technique of an elite triathlete in relation to training practices.

Within Chapters 3 and 4 additional factors, not addressed in previous studies (running experience prior to taking up triathlon and gender), were considered in order to develop a more detailed understanding of triathlete running technique. The latter chapters of this thesis combined the theoretical understanding gathered in Chapters 3 and 4 along with previously documented findings, to design and implement intervention programmes aimed at modify running technique in triathletes. With the intent of exploring whether alteration of running technique may be beneficial to triathletes, the effect of flexibility training and technique drills training were examined.

The final empirical chapter of this thesis (Chapter 7) provided a novel insight into the running technique of an elite female triathlete through 18 months of her training schedule. Running technique adaptations in response to differing training demands and the constraints of working with elite performers were addressed.

The findings of this thesis will now be discussed in relation to coordination in triathletes, gender specific considerations and training implications.

8.2 **Coordination of triathlete running technique**

Previous findings relating to the running kinematics of triathletes indicate that triathletes exhibit both short term (Hausswirth et al., 1997; Gottschall and Palmer, 2000; Millet and Vleck, 2000 and Millet et al., 2001) and long term (Connick, 2009) running adaptations in response to cycling. The primary aim of this thesis was to further explore these long-term adaptations.

Previous findings relating to the running kinematics of triathletes indicate that triathletes exhibit shorter relative strides and decreased hip ROM, thigh extension and anterior pelvic tilt in comparison to runners (Connick, 2009). These authors of the aforementioned study proposed that these adaptations occur as a result of the large volumes of cycling typically undertaken by triathletes (O'Toole, 1989) and the lack of running experience triathletes have in comparison to pure runners. In order to confirm or reject these assumptions, we compared in Chapter 3 the running technique of both triathletes and runners to that of cyclists and triathletes who had trained as pure runners prior to taking up triathlon. In addition, in Chapter 4 we sought to investigate whether the differences found between male runners and triathletes also occurred in female populations.

Previous findings regarding the differences in running technique between triathletes and runners (Connick, 2009) were replicated in males in Chapter 3 of this thesis. Furthermore, results of Chapter 4 revealed that, in spite of gender differences in running (Chumanov et al., 2008; Schache et al., 2003; Ferber et al., 2003; Malinzak et al., 2001; Williams et al., 1987) and cycling technique (Sauer et al., 2007; Potter et al., 2008), female triathletes also demonstrated shorter relative strides and decreased hip extension, thigh extension and pelvic tilt in comparison to their running counterparts. Such findings add further support to the supposition that the running technique differences between triathletes and runners are as a result of the long term adaptations to the multifaceted nature of triathlon. It also suggests that in spite of gender specific difference noted above female and male adaptations to cycling are more alike than different.

Additional findings in Chapter 3 regarding the running technique of pure cyclists also substantiated the postulated contributory effect of cycling in the running adaptations displayed by triathletes. Specifically, cyclists exhibited running kinematics least like that of runners, and as these differences occurred in the same parameters as when triathletes are compared to runners it was surmised that the volume of cycling undertaken by triathletes is the cause of their modified running technique.

Such findings may be of great importance to triathletes and their coaches as maximal endurance running performance is affected by both aerobic and biomechanical factors (Slawinski and Billat, 2004). Previous findings relating to the importance of pelvic tilt, hip extension and thigh extension in directing propulsive forces along the transverse axis of the leg in an efficient horizontal direction (Chang and Kram, 1999; Chang et al., 2000; Novacheck, 1998) suggest that the adaptations in triathlete running technique may have a detrimental effect on their running performance. However, an alternative explanation of the differences between triathletes and runners may be that running technique is modified due to muscular adaptations to allow optimal performance throughout the entire multidiscipline event rather than each individual discipline (Chapman et al., 2004).

Findings from Chapter 3 also showed that triathletes from a running background exhibited differences in running kinematics when compared to runners but not in comparison to triathletes. This finding not only adds further support to the link between adapted running kinematics and cycling, but also suggests that the increased running ability when starting out in triathlon level out when cycling is undertaken as part of triathlon training. Whilst more research is required to address the time frame over which these changes in coordination occur, the tendency of running technique to change in response to the addition of new tasks is an important finding for beginner and experienced triathletes. Issues surrounding the prevention and minimisation of such technique changes are addressed in the ‘Implications for training’ section of this chapter (8.4).

Whilst addressing both the chronic and acute running adaptations to triathlon appears to provide a comprehensive overview of the running adaptations that occur in triathletes, findings in Chapter 7 (the longitudinal case study of an elite triathlete) highlight another intermediate adaptation to triathlon training. Specifically, in the participant studied, running technique changes appeared to occur due to changes in training demands and relative volumes of training in each discipline undertaken during training cycles. These changes took place although no specific technique training was implemented and no technical change was expected or sought. Although this case-study only presented results in relation to one, elite participant, the change of running technique in response to training demands may have important implications the wider triathlete population. Such findings may highlight important issues in relation to previously documented long term adaptations and the balance of disciplines during training. If, indeed, technique does change throughout the season in other triathlete populations, then the phase of season and training regime of participants at the time of testing should be carefully considered in the interpretation of findings relating to triathlete running technique.

Within the context of this thesis, the effect of altered coordination as a result of triathlon training has only been considered in respect to the single element of running. Although, given the relationship of the running phase and overall triathlon performance this is justified, results yielded from Chapter 7 concerning the effect of training on technique also highlight the need for examination of training factors on other disciplines. The proposed effect of cycling training on the modification of running technique has been addressed throughout this thesis. However, the effect of altered coordination, in respect to the other disciplines, has not been addressed. For example, increased cycling may have an effect on shoulder flexibility which, in turn, may influence coordination during swimming.

Reviewed in combination with previous literature, Chapters 3, 4 and 5 provide an insight into the different types of adaptations triathletes go through in response to triathlon. Future research may seek to expand the findings of Chapter 7 to larger populations, examining the effect of training ratios and volumes on running technique. Further research may also address the influence of differing training regimes not only on running technique, but also the effect they have on cycling and swimming technique.

8.3 **Gender specific considerations**

Along with the vast majority of literature surrounding running technique in triathlon, the findings of Chapter 3 and those of Connick (2009) relate only to males. In order to address this gap, Chapter 4 sought to investigate whether the differences found between male runners and triathletes also occurred in female populations. Results revealed that, in spite of gender differences in running (Chumanov et al., 2008; Schache et al., 2003; Ferber et al., 2003; Malinzak et al., 2001; Williams et al., 1987) and cycling technique (Sauer et al., 2007; Potter et al., 2008), female triathletes demonstrated the same adaptations to triathlon as previously documented in males. Such a finding has important implications for programmes that seek to modify the running technique of triathletes, as given the similar nature of the adaptations to triathlon irrespective of gender, interventions designed to modify running technique in triathletes could be aimed at both males and females. Interpretation of data pertaining to the long term adaptations of running technique in both males and females, whilst considering their different anatomical constraints, may also provide greater insight to the causes of these adaptations.

Chapter 4 also raises the important point of injury aetiology in respect to the adaptations both male and female triathletes display. Given that male and female runners are likely to suffer from different injuries to one another (Schache et al., 2003; Ferber et al., 2003) and that triathlon training appears to further exacerbate some of the previously documented gender differences in running technique, male triathletes may be more susceptible to injuries typically seen in female runners rather than those in male runners. More research into the links between multidisciplinary training (such as that undertaken by triathletes), gender and injury aetiology is recommended.

Although the similarities between male and female adaptations to triathlon look similar, the effect of increased training may cause gender specific outcomes. If, for example, the way males increase their power during cycling differs from females (increasing force per pedal stroke rather that cadence for example) it may be the case that adaptations in running technique in response to increased cycling velocity result in gender specific adaptations to increase cycling power. Further research to examine gender specific responses to altered training and to power production in cycling is required.

Whilst these results provide an insight in to the running technique of female triathletes, there are a number of potential confounding factors left unexplored. For example data surrounding the effect of stage of menstruation cycle on flexibility is inconclusive (Hinnerichs et al., 2004). Variations in flexibility due to this may therefore have an impact on the running technique in females. Future studies could address this by examining these factors in triathletes.

8.4 Implications for training

The latter chapters of this thesis aimed to combine the theoretical understanding gathered in Chapters 3 and 4 along with previously documented findings, and utilise it to design and implement intervention programmes in order to investigate whether the modification of running technique in triathletes may be beneficial.

Measures of hip extension flexibility carried out in Chapter 3 indicated that runners have significantly more hip extension capability than triathletes and cyclists and that in populations with restricted flexibility (triathletes and cyclists) these clinical measures are correlated with kinematic measures. Given that static ROM can be increased by a flexibility programme (Christiansen, 2008; DiBendetto et al., 2005; Watt et al., 2009; Winters et al., 2004) in Chapter 5 we sought to investigate whether increasing static hip extension capability could counteract the lack of flexibility found in the hip flexors of triathletes and subsequently elicit changes in their running kinematics. Whilst significant improvements in the static hip ROM showed that the flexibility intervention was successful, this did not result in significant changes to the running kinematics (stride length, thigh extension, dynamic hip ROM and pelvic tilt). It was concluded that flexibility alone is not sufficient to change running technique in triathletes and that flexibility programmes should be complemented by specific training. Consequently, in Chapter 6 we sought to investigate the combination of a flexibility programme alongside a running technique drills programme. However, the running technique drills failed to bring about any modifications in running kinematics and consequently it is yet is be confirmed whether refinement of running technique together with increased hip flexibility can bring about changes in the running technique of triathletes. This study highlights the need for research in to the efficacy of common training drills used for developing running technique.

The results of Chapter 6, in no way means that drills should not be used in training. However they do highlight that the specific drills used, did not work in the specific population of Chapter 6. Moreover issues with the volume and type of drills may have affected their effectiveness although the drills used were prescribed by an experienced triathlon coach and the protocol involved a greater volume than is normally prescribed in triathlete training programmes. Furthermore 50% of the drills sessions involved high levels of supervision, meaning they were carried out correctly.

It can be concluded, from the intervention studies in this thesis (Chapters 5 and 6), that changing running technique is not as simple as a structured flexibility programme or drills sessions, even in combination. Whilst it could be suggested that in an embedded skill such as running technique is unlikely to be easily changed, results from Chapter 7 indicate that, even in an elite triathlete, running technique does change throughout the season. Furthermore, the addition of cycling to an experienced runner’s training regime when taking up triathlon also appears to cause long term changes in running technique (Chapter 3). The question of whether more and/or different flexibility and technique training has an effect on running kinematics merit further investigation.

In respect to the changing technique of a runner taking up triathlon, interventions to restrict the adaptations to the addition of cycling may prove more effective than interventions to reverse such adaptations. Preventing or minimising such immediate adaptations may be advantageous in that runners could maintain their superior running ability in comparison to pure triathletes; conversely, such interventions may restrict improvements in cycling.

Results from Chapter 7 indicate that the timing of implementing intervention programmes should also be considered. For example a hip flexibility programme may be implemented during a training phase involving high levels of cycling in an attempt to minimise the effect this training may have on running technique. Moreover, there may be times of the training year when technique is more adaptable than others. These suggestions also highlight the importance of controlling, as much as possible, the training regime of participants taking part in intervention studies. Furthermore, future papers should present in what part of the training cycle the experiment has been conducted.

In discussing the modification of running technique through intervention programmes, it is pertinent to raise the point that running technique modification may occur as a result of adaptations to allow optimal performance throughout the entire multidiscipline event of triathlon rather than each individual discipline (Chapman et al., 2004). Had the interventions implemented in Chapters 5 and 6 been successful at changing the running technique of triathletes the next important step would have been to examine whether these changes did have the anticipated positive effect on running performance and what effect such changes had on cycling performance.

8.5 **Limitations**

Although some important findings have been reported with regards to the running kinematics of triathletes, it is pertinent to address some of the limitations that feature throughout the empirical chapters of this thesis.

Observations in all of the studies were based on treadmill running. Whilst this decreased some of the ecological validity, it enabled well-standardised, easily repeatable data collection. The use of treadmills in such research has been cause for concern due to the potential differences in kinematics between treadmill running and overground running (Schache et al., 2001). However, other authors have reported no such differences at velocities similar to the velocities tested in this study (Riley, 2008; Schache et al.,2001; Williams 1985). These inconsistent findings may be as a result of the differing mechanical properties of the treadmill surfaces used in the individual studies (Schache et al., 2001) therefore, to minimize this potential problem, the same treadmill was used for data collection throughout all of the presented chapters. Furthermore, the use of a treadmill for data collections in this thesis allowed comparison between groups in identical conditions.

Marker movement artefact is a common problem within kinematic data collections such as those presented in this thesis and is particularly pertinent when making comparisons of data between sessions (Chapman et al., 2009). Analysis of only sagittal plane data avoided the increased error associated with transverse and frontal plane movements (Chapman et al., 2009). However, measures of pelvic tilt are still susceptible to marker misplacement errors (Schache et al., 2002), however such errors are liable to be equal for all groups tested, and as such, these systematic errors are not likely to affect comparisons between groups. Furthermore, in order to maintain as much consistency in data collection proceedings, marker placements were carried out by the same experimenter.

With regards to the flexibility measures, the lack of experimenter blinding to either which group the participant was in (Chapter 3) or to the prescription of an intervention programme (Chapters 5 and 6) may have resulted in bias of these measures. In order to minimise this effect, all participants received the same instruction to stretch maximally and always had the non-test limb held to their chest by another experimenter. Furthermore, between tests in Chapters 4 and 5, the experimenter did not examine any of the data relating to the participants' flexibility. The flexibility measures have also been shown to be highly repeatable between days (Chapter 2), however, future studies may consider blinding the experimenters as to the different backgrounds of participants to minimise any potential bias affecting results.

Throughout this thesis, participant numbers were restricted, not only as a result of the availability of sports people who conformed to sets of stringent inclusion criteria (training volume, experience and injury status), but also their willingness to have their training regimes altered (Chapters 5 and 6). The author acknowledges that the relatively low participant numbers, particularly within the intervention studies (Chapters 5 and 6) could have led to either a Type 1 error (rejection of a null hypothesis that is actually true) or a Type 2 error (failure to reject a null hypothesis that should be rejected). Power analyses could have been used to assess the number of participants needed to minimise the chance of such errors, however, given the aforementioned factors restricting participant recruitment, it was accepted that the ideal number of participants was unlikely to be met. Nevertheless, in spite of the limited participant numbers, the lack of any trends, of any magnitude, within the findings of the intervention studies (Chapters 5 and 6) imply that larger participant numbers were unlikely to elicit any changes.

One factor not considered in the series of studies in this thesis is the variety of distances over which triathlon is competed. Running technique is liable to be different between competitors who compete over for example the marathon distances associated with Ironman and the far shorter distances in sprint distance races. Furthermore the volume of cycling training and in turn the influence this may have on running technique will be dependent upon the distances over which the triathlete competes. In order to allow maximum participant recruitment for all cohort studies (apart from Chapter 5) no stipulation was placed on what distances participants were accustomed. Further research is required to address such differences.

8.6 **Conclusions**

To conclude, this thesis set out to further explore previously documented, chronic adaptations to triathlon and to apply this theoretical understanding to design and implement intervention programmes to modify the running technique used by triathletes. The application of this theory into practice was also used to assess the running technique of an elite triathlete in relation to training practices.

Results of this thesis reveal that the previously reported, long term, running technique differences appear not only between male triathletes and runners but also with females. Adding further support to the previously postulated link between the volume of cycling undertaken by triathletes and these running technique differences, it was also found that the differences between triathletes and runners were magnified in cyclists. Triathletes from a running background also exhibited differences in running kinematics when compared to runners but not in comparison to triathletes indicating that increased running ability when starting out in triathlon may level out when cycling is undertaken as part of triathlon training

Measures of hip extension flexibility carried out in Chapter 3 indicate that limited active hip extension during running in cyclists and triathletes may be linked to restrictions in these clinical measures. Consequently the effect of a hip flexor flexibility programme on running performance in triathletes was examined. Whilst the programme was effective at increasing static ROM, these changes were not translated to running performance. Thus, results suggest that the differences between running performance in triathletes and runners may not be solely due to tight hip flexors and that instruction to improve their running technique may enable them to utilise the newly available ROM effectively. However, in a subsequent study, running technique drills failed to bring about any modifications in running kinematics and it is therefore yet to be confirmed whether refinement of running technique together with increased hip flexibility can bring about positive changes in the running technique of triathletes.

In depth analysis of the running technique of an elite female triathlete through 18 months of her training schedule allowed a novel insight into the biomechanical factors affecting elite triathlete performance. This study brought together theoretical knowledge and applied it in such a way that highlighted the potential performance benefits of such understanding. Tying in with previous chapters, the proposed relationship between long term running adaptations to cycling in triathletes were noticed, even in a world class athlete. Future research should seek to build up a case by case picture of the long and short term effects of training in triathletes of varying ability to enable potentially performance enhancing findings to be ascertained without the risk of adversely affecting elite performance.

Appendix A: PRE-TEST QUESTIONNAIRES

The University of Birmingham
School of Sport and Exercise Sciences
General Health Questionnaire

Name: ....
Address: ....
....
....
Phone: ....

Name of the responsible investigator for the study:

....

Please answer the following questions. If you have any doubts or difficulty with the questions, please ask the investigator for guidance. These questions are to determine whether the proposed exercise is appropriate for you. Your answers will be kept strictly confidential.

1.	You are.......	Male	Female
2.	What is your exact date of birth? Day........... Month...........Year..19........ So your age is........................... Years		
3.	When did you last see your doctor? In the: Last week............ Last month.......... Last six months............ Year................. More than a year...........		
4.	Are you currently taking any medication?	YES	NO
5.	Has your doctor ever advised you not to take vigorous exercise?	YES	NO
6.	Has your doctor ever said you have “heart trouble”?	YES	NO
7.	Has your doctor ever said you have high blood pressure?	YES	NO
8.	Have you ever taken medication for blood pressure or your heart?	YES	NO
9.	Do you feel pain in your chest when you undertake physical activity?	YES	NO
10.	In the last month have you had pains in your chest when not doing any physical activity?	YES	NO
11.	Has your doctor (or anyone else) said that you have raised blood cholesterol?	YES	NO
12.	Have you had a cold or feverish illness in the last month?		

		YES	NO
13.	Do you ever lose balance because of dizziness, or do you ever lose consciousness?	YES	NO
14.	a) Do you suffer from back pain b) if so, does it ever prevent you from exercising?	YES YES	NO NO
15.	Do you suffer from asthma?	YES	NO
16.	Do you have any joint or bone problems which may be made worse by exercise?	YES	NO
17.	Do you have/have you had previously any injuries to your lower limbs?	YES	NO
18.	Has your doctor ever said you have diabetes?	YES	NO
19.	Have you ever had viral hepatitis?	YES	NO
20.	If you are female, to your knowledge, are you pregnant?	YES	NO
21.	Do you know of any reason, not mentioned above, why you should not exercise?	YES	NO
22.	Are you accustomed to vigorous exercise (an hour or so a week)?	YES	NO
23.	What sporting activities do you regularly participate in?		

I have completed the questionnaire to the best of my knowledge and any questions I had have been answered to my full satisfaction.

Signed: ....

Date: ....

The University of Birmingham
School of Sport and Exercise Sciences
Sport Specific Questionnaire

Name: ....

Please answer the following questions. If you have any doubts or difficulty with the questions, please ask the investigator for guidance. These questions are to determine your level of skill and experience in each discipline. Your answers will be kept strictly confidential.

1.	At which of the following sports have you competed?	*Swimming / Cyling / Running / Triathlon*	
2.	How many years have you been training/racing?	*…………Years training* *…………Years racing*	
3.	At what level/category do you compete?	*eg local races, national, international etc.*	
4.	At which distances have you competed?	*Please include triathlon distances, run races and cycle time trials- whichever are applicable*	
5.	What are your documented PB times for the above distances?	*Please include cycle time trial PBs, run race PBs and triathlon PBs*	
6	What are your typical weekly training mileages and hours?	*Bike and run if triathlete*	
7.	Are you attached to a club?	*YES*	*NO*
8a.	Runners, do you regularly cycle?	*YES*	*NO*
8b.	If you answered yes to question 7a,	*Please provide details.volume, part of training, mode of transport etc?*	
9	Do you regularly carry out any form of drills or flexibility?	*Please provide details, specifc drills, focus of flexibility, frequency, volume etc*	

Appendix B: PARTICIPANT INFORMATION

The participant information forms that were provided in Chapters 3 and 4 were similar to one another and are therefore combined below. { } indicate where slightly different information was provided to female participants in Chapter 4.

UNIVERSITY OF BIRMINGHAM

Human Performance Laboratory

FURTHER EXPLORATION OF RUNNING KINMATICS IN TRIATHLETES

Participant Information

Thank you for your interest in participating in this study.

What is this study investigating?

This study aims to investigate whether triathletes exhibit different running styles to runners, runners who became triathletes and cyclists.

{This study aims to investigate whether female triathletes exhibit different running styles to female runners.}

How long is the test session?

You will be required to visit the laboratory on 1 occasion; this session should last no longer than 1 hour.

All participants are free to withdraw from the study at any time without the need for explanation. If this is your decision, please inform us as soon as possible.

What do I have to do?

Running Technique Analysis

Following a warm up you will be requested to complete 3 x 2 minute bouts of running on a treadmill at a range of randomly assigned speeds between 13 and 17 km/h {11 and 15 km/h}. Bouts will be separated by a 3-5 minute recovery period.

What other data is being collected and how will it be used?

We will be recording the positions of small reflective markers placed on your joints using double sided sticky tape. Our equipment will record the 3D positions of these markers.

With this method of recording your motion, we try to eliminate all other sources of reflection from the experimental area. We will ask you to remove items of jewellery (e.g. rings, watches, bracelets, etc.), and will cover any areas of reflective material on your clothing with tape. Please avoid wearing *clothing with large areas that are reflective. We would also like you to wear shorts and a t-shirt if possible.*

<u>All data is treated anonymously, and any data used in publication will remain anonymous.</u>

Where do I need to go for testing?
You will be tested in the Kinesiology Lab in the School of Sport and Exercise Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT.

What if I have any other questions or concerns?
Please contact us on the details below:
Contact details were provided here

The participant information forms that were provided in Chapters 5 and 6 were similar to one another and are therefore combined below. { } indicate where additional information was provided to participants in Chapter 6.

UNIVERSITY OF BIRMINGHAM

Human Performance Laboratory

FLEXIBILITY AND DRILLS TRAINING IN TRIATHLON

Participant Information Sheet

Thank you for your interest in participating in this study.

What is this study investigating?

This study aims to investigate the effect of running technique drills and a stretching programme on triathlon running performance.

How long is the test session?

You will be requested to attend the lab 4 times {5 times} with each session lasting no more than 1 hour. {You will also be asked to attend a drills session twice a week (run during on of your normal training sessions)}. In addition to this you will be given a flexibility intervention programme to carry out 3 times a week for 8 weeks, these sessions should last no more the 45 minutes.

<u>All participants are free to withdraw from the study at any time without the need for explanation. If this is your decision, please inform us as soon as possible.</u>

What do I have to do?

Lab visits will be made up of the following subsections:

Static Hip Range of Motion (ROM) Analysis

This will be assessed using the modified Thomas test. This test requires lay back on a plinth with one leg held close to your chest and the other dropped over the edge. A device will be used to measure the angle of extension of the hanging leg. These tests are painless and will be carried out by a trained experimenter.

Running Technique Analysis

Following a warm up you will be requested to complete 3 x 2 minute bouts of running on a treadmill at a range of randomly assigned speeds between 13 and 17 km/h. Bouts will be separated by a recovery period.

All lab sessions will involve Static Hip ROM and Running Technique Analysis.

What other data is being collected and how will it be used?

In addition to hip ROM data, we will be recording the positions of small reflective markers placed on your joints using double sided sticky tape. Our equipment will record the 3D positions of these markers.

With this method of recording your motion, we try to eliminate all other sources of reflection from the experimental area. We will ask you to remove items of jewellery (e.g. rings, watches, bracelets, etc.), and will cover any areas of reflective material on your clothing with tape. Please avoid wearing clothing with large areas that are reflective. We would also like you to wear shorts and a t-shirt if possible.

All data is treated anonymously, and any data used in publication will remain anonymous.

Interventions

{Following the first lab session you will be asked to take part in an 8 week technique drills programme to be carried out a twice times a week. These sessions will last no longer than 30 minutes and 1 session per week will be carried out under the supervision of your coach alongside your normal group running sessions. You will be provided with a training manual with details of the exercises and a training diary to note down when you train and any comments you have about the session. You will also be provided with a url where videos of the drills can be found}

In addition to this, following the second {third} lab session you will be given an 8 week flexibility programme to carry out 3 times a week on non-consecutive days. The sessions will last no more than 45 minutes.

The first flexibility session will take place in the lab with instruction, demonstration and monitoring from the experimenters. You will be provided with a training manual with details of the exercises and a training diary to note down when you train and any comments you have about the session. In addition, throughout the programme a tester will be present for one flexibility session per week; this will be at your convenience and will allow testers to analyse exercise technique and progression through the exercise programme.

Where do I need to go for testing?

You will be tested in the Kinesiology Lab in the School of Sport and Exercise Sciences, University of Birmingham, Edgbaston, Birmingham. B15 2TT.

What if I have any other questions or concerns?

You can contact us on the details below:

Contact details were provided here.

Appendix C: PARTICIPANT CONSENT FORMS

UNIVERSITY OF BIRMINGHAM

Human Performance Laboratory

School of Sport and Exercise Sciences

Participant Consent Form

Investigation:

<Study title inserted here>

Investigators: Miss Amy Scarfe

Dr François-Xavier Li

Participant:

Name ....

Address ....

....

....

....

....

Date of Birth ....

I have read the attached Information sheet and discussed the investigation with.......................... ....who has explained the procedures to my satisfaction. I am willing to undergo the investigation but understand that I am free to withdraw at any time without having to give an explanation and that doing so will not affect any treatment or care I may receive.

Signed ....

Witnessed ....

Date ....

Appendix D: SUPPLEMENTARY DATA

Table D1: Stride length measures ± SD (m) for Chapter 3.

	Cyclists	Tri Run	Triathletes	Runners
13	2.33 ± 0.14	2.48 ± 0.15	2.39 ± 0.15	2.64 ± 0.07
15	2.65 ± 0.17	2.77 ± 0.16	2.70 ± 0.18	2.96 ± 0.10
17	2.85 ± 0.15	3.08 ± 0.18	2.95 ± 0.20	3.27 ± 0.11

Table D2: Relative stride length measures ± SD (m) for Chapter 3.

	Cyclists	Tri Run	Triathletes	Runners
13	2.61 ± 0.13	2.77 ± 0.17	2.67 ± 0.19	2.94 ± 0.23
15	2.97 ± 0.16	3.10 ± 0.17	2.99 ± 0.22	3.24 ± 0.21
17	3.17 ± 0.14	3.44 ± 0.19	3.30 ± 0.20	3.58 ± 0.22

Table D3: Stride rate measures ± SD (Hz) for Chapter 3.

	Cyclists	Tri Run	Triathletes	Runners
13	1.43 ± 0.07	1.39 ± 0.08	1.40 ± 0.08	1.37 ± 0.04
15	1.48 ± 0.09	1.43 ± 0.09	1.46 ± 0.09	1.41 ± 0.05
17	1.53 ± 0.10	1.46 ± 0.09	1.51 ± 0.11	1.45 ± 0.05

Table D4: Peak hip extension measures ± SD (deg) for Chapter 3.

	Cyclists	Tri Run	Triathletes	Runners
13	2.32 ± 1.04	4.52 ± 3.78	3.58 ± 2.92	5.28 ± 4.06
15	4.80 ± 1.77	5.66 ± 3.68	4.85 ± 2.98	6.39 ± 4.19
17	6.34 ± 2.17	7.33 ± 3.54	6.94 ± 2.96	7.95 ± 3.96

Table D5: Peak thigh extension measures ± SD (deg) for Chapter 3.

	Cyclists	Tri Run	Triathletes	Runners
13	72.61 ± 3.02	68.31 ± 3.04	69.49 ± 2.65	66.38 ± 2.08
15	70.76 ± 3.47	66.64 ± 2.99	67.33 ± 2.62	63.33 ± 3.60
17	68.97 ± 2.84	64.68 ± 2.99	65.50 ± 3.31	62.15 ± 2.77

Table D6: Peak anterior pelvic tilt measures ± SD (deg) for Chapter 3.

	Cyclists	Tri Run	Triathletes	Runners
13	12.31 ± 3.78	15.41 ± 4.01	13.81 ± 3.27	21.58 ± 2.28
15	13.42 ± 3.97	16.69 ± 4.27	15.49 ± 2.89	22.46 ± 2.16
17	14.92 ± 4.31	17.75 ± 4.33	16.66 ± 2.90	23.49 ± 2.34

Table D7: Stride length measures ± SD (m) for Chapter 4.

	Runners	Triathletes
11	2.21± 0.10	2.17 ± 0.08
13	2.53 ± 0.14	2.51 ± 0.11
15	2.82 ± 0.15	2.74 ± 0.18

Table D8: Relative stride length measures ± SD (m) for Chapter 4.

	Runners	Triathletes
11	2.51 ± 0.15	2.41 ± 0.08
13	2.88 ± 0.16	2.80 ± 0.13
15	3.20 ± 0.16	3.05 ± 0.15

Table D9: Stride rate measures ± SD (Hz) for Chapter 4.

	Runners	Triathletes
11	1.39 ± 0.07	1.41 ± 0.05
13	1.43 ± 0.08	1.44 ± 0.06
15	1.48 ± 0.09	1.51 ± 0.06

Table D10: Peak hip extension measures ± SD (deg) for Chapter 4.

	Runners	Triathletes
11	0.73 ± 4.96	0.43 ± 4.21
13	3.02 ± 5.37	1.92 ± 4.12
15	5.24 ± 5.44	4.33 ± 4.10

Table D11: Peak thigh extension measures ± SD (deg) for Chapter 4.

	Runners	Triathletes
11	65.32 ± 3.85	69.39 ± 1.77
13	62.54 ± 3.93	66.66 ± 1.69
15	59.90 ± 4.38	64.62 ± 1.81

Table D12: Peak anterior pelvic tilt measures ± SD (deg) for Chapter 4.

	Runners	Triathletes
11	24.79 ± 5.44	21.59 ± 4.77
13	25.87 ± 5.21	22.57 ± 4.14
15	26.67 ± 4.72	23.52 ± 4.20

Table D13: Static hip flexibility measures ± SD (deg) for Chapter 5.

	Week -4	Week 0	Week 4	Week 8
IP	-3.59 ± 1.94	-5.00 ± 1.82	2.41± 1.56	4.15 ± 1.77
RF	-17.63 ± 3.48	-17.93 ± 2.43	-8.56 ± 2.83	-5.07 ± 2.00

Table D14: Stride length measures ± SD (m) for Chapter 5.

	Week -4	Week 0	Week 4	Week 8
13	2.57 ± 0.17	2.58 ± 0.19	2.58 ± 0.15	2.59 ± 0.14
15	2.89 ± 0.21	2.89 ± 0.23	2.90 ± 0.19	2.91 ± 0.18
17	3.18 ± 0.29	3.16 ± 0.26	3.19 ± 0.25	3.20 ± 0.24

Table D15: Stride rate measures ± SD (Hz) for Chapter 5.

	Week -4	Week 0	Week 4	Week 8
13	1.41 ± 0.10	1.41 ± 0.10	1.39 ± 0.11	1.38 ± 0.10
15	1.45 ± 0.11	1.45 ± 0.12	1.43 ± 0.12	1.44 ± 0.11
17	1.51 ± 0.10	1.49 ± 0.13	1.48 ± 0.11	1.48 ± 0.13

Table D16: Peak hip extension measures ± SD (deg) for Chapter 5.

	Week -4	Week 0	Week 4	Week 8
13	3.92 ± 2.91	3.88 ± 2.67	3.95 ± 2.30	4.13 ± 2.01
15	5.75 ± 2.99	5.68 ± 2.98	6.01 ± 2.53	5.99 ± 2.26
17	7.69 ± 3.18	7.55 ± 2.77	8.01 ± 2.52	7.87± 2.56

Table D17: Peak thigh extension measures ± SD (deg) for Chapter 5.

	Week -4	Week 0	Week 4	Week 8
13	69.37 ± 3.64	69.77 ± 3.65	70.34 ± 3.21	68.71 ± 3.74
15	66.39 ± 5.56	66.23 ± 4.54	67.33 ± 3.83	65.94 ± 3.39
17	64.16 ± 2.84	63.81 ± 2.99	64.11 ± 3.31	63.90 ± 2.77

Table D18 Peak anterior pelvic tilt measures ± SD (deg) for Chapter 5.

	Week -4	Week 0	Week 4	Week 8
13	13.30 ± 2.96	13.25 ± 3.46	13.05 ± 3.63	13.09 ± 3.69
15	14.95 ± 2.87	14.74 ± 3.04	14.77 ± 3.22	14.84 ± 3.26
17	16.54 ± 3.29	16.38 ± 3.56	16.54 ± 3.63	16.66 ± 3.63

Table D19: Static hip flexibility measures ± SD (deg) for Chapter 6.

	Week 0	Week 4	Week 8	Week 12	Week 16
IP	-17.63 ± 3.48	-17.63 ± 3.48	-17.93 ± 2.43	-8.56 ± 2.83	-5.07 ± 2.00
RF	-4.41 ± 2.70	-3.19 ± 2.31	-4.52 ± 2.23	3.19 ± 1.70	5.00 ± 2.37

Table D20: Stride length measures ± SD (m) for Chapter 6.

	Week 0	Week 4	Week 8	Week 12	Week 16
13	2.56 ± 0.12	2.54 ± 0.13	2.54 ± 0.14	2.57 ± 0.13	2.57 ± 0.13
15	2.85 ± 0.15	2.85 ± 0.14	2.85 ± 0.15	2.87 ± 0.16	2.86 ± 0.14

Table D21: Relative stride length measures ± SD (m) for Chapter 6.

	Week 0	Week 4	Week 8	Week 12	Week 16
13	2.71 ± 0.16	2.71 ± 0.13	2.71 ± 0.15	2.73 ± 0.11	2.72 ± 0.12
15	3.01 ± 0.15	3.02 ± 0.15	3.01 ± 0.16	3.02 ± 0.15	3.02 ± 0.17

Table D22: Stride rate measures ± SD (Hz) for Chapter 6.

	Week 0	Week 4	Week 8	Week 12	Week 16
13	1.41 ± 0.08	1.42 ± 0.09	1.42 ± 0.07	1.39 ± 0.08	1.40 ± 0.08
15	1.46 ± 0.09	1.46 ± 0.08	1.45 ± 0.10	1.45 ± 0.07	1.45 ± 0.08

Table D23: Peak hip extension measures ± SD (deg) for Chapter 6.

	Week 0	Week 4	Week 8	Week 12	Week 16
13	3.56 ± 4.03	3.54 ± 3.74	3.68 ± 3.31	3.72 ± 3.41	3.77 ± 2.88
15	5.91 ± 4.62	5.58 ± 5.87	5.62 ± 4.03	6.05 ± 3.01	5.95 ± 3.17

Table D24: Peak thigh extension measures ± SD (deg) for Chapter 6.

	Week 0	Week 4	Week 8	Week 12	Week 16
13	68.66 ± 2.20	67.91 ± 2.31	67.70 ± 3.17	68.00± 2.92	67.95 ± 1.66
15	65.30 ± 3.14	65.94 ± 3.65	66.21 ± 3.84	65.33± 3.70	66.91 ± 2.19

Table D25: Peak anterior pelvic tilt measures ± SD (deg) for Chapter 6.

	Week 0	Week 4	Week 8	Week 12	Week 16
13	12.21 ± 4.46	12.04 ± 4.49	12.56 ± 5.91	12.20 ± 6.76	12.71 ± 5.81
15	14.72 ± 6.22	15.23 ± 4.50	15.37 ± 6.03	15.06 ± 7.24	15.04 ± 5.87

REFERENCES

Arendse, R.E., Noakes, T.D., Azevedo, L.B., Romanov, N., Schwellnus, M.P. and Fletcher, G. (2003). Reduced eccentric loading of the knee with the Pose Method running. *Medicine and Science in Sports and Exercise,* 36, 272-277.

Backman, C.L. and Harris, S.R. Case studies, single-subject research and N of 1 randomized trials: comparisons and contrasts. *American Journal of Physical Medicine and Rehabilitation,* 78, 170-176.

Bentley, D.J., Millet, G.P., Vleck, V.E. and McNaughton, L.R. (2002). Specific aspects of contemporary triathlon: implications for physiological analysis and performance. *Sports Medicine,* 32, 435-459.

Bernard, T., Vercruyssen, F., Grego, F., Hausswirth, C., Lepers, R., Vallier, J. M. and Brisswalter, J. (2003). Effect of cycling cadence on subsequent 3km running performance in well trained triathletes. *British Journal of Sports Medicine*, 37, 154-58.

Bezodis, I.N., Salo, A.I.T. and Kerwin, D.G. (2008). A longitudinal case study of step characteristics in a world class sprint athlete. 26th International Symposium on Biomechanics in Sports, (Eds. Kwon, Y-H., Shim, J., Shim, J.K. and Shin, I.-S.). Seoul, Korea, July 14th-18th.

Bonacci, J., Green, D., Saunders, P.U., Blanch, P., Franettovich, M., Chapman, A.R. et al., (2010a). Changes in running kinematics after cycling are related to alterations in running economy in triathletes. *Journal of Science and Medicine in Sport,* 13, 460-464.

Bonacci, J., Blanch, P., Chapman, A.R and Vicenzino, B. (2010b). Altered movement patterns but not muscle recruitment in moderately trained triathletes during running after cycling. *Journal of Sports Sciences,* 28, 1477-1487.

Bosch, F., & Klomp, R. (2005). *Running: Biomechanics and exercise physiology applied in practice.* Maarssen, The Netherlands: Elsevier Limited.

Callaghan, M. J. (2005). Lower body problems and injury in cycling. *Journal of Bodywork and Movement Therapies,* 9, 226-236.

Cameron, M.L. Adams, R.D., Maher, C.G. and Misson, D. (2009). Effect of the HamSprint drills training programme on lower limb neuromuscular control in Australian football players. *Journal of Science and Medicine in Sport,* 12, 24-30.

Cavanagh, P.R. and Williams, K.R. (1982). The effect of stride length variation on oxygen uptake during distance running. Medicina and Science in Sports and Exercise, 14, 30-35.

Cavanagh, P.R., Pollock, M.L., and Landa, J. (1977). A biomechanical comparison of elite and good distance runners. *Annals of the New York Academy of Sciences*, 301, 328-345.

Chang, Y. H., Huang, H. W., Hamerski, C. M., and Kram, R. (2000). The independent effects of gravity and inertia on running mechanics. *Journal of Experimental Biology*, 203, 229-238.

Chang, Y. H. and Kram, R. (1999). Metabolic cost of generating horizontal propulsive forces during human running. *Journal of Applied Physiology*, 86 1657-1662.

Chapman, A.R., Hodges, P.W., Briggs, A.M., Stapley, P.J. and Vicenzino, B. (2010). Neuromuscular control and exercise related leg pain in triathletes. *Medicine and Science in Sports and Exercise*, 42, 233-243.

Chapman, A., Vicenzino, B., Hodges, P.W., Blanch, P., and Hahn, A. (2009). A protocol for measuring the effect of cycling on neuromuscular control of running. *Journal of Sports Sciences,* 27, 767-782.

Chapman, A,R., Vincenzio, B., Blanch, P., Dowlan, S. and Hodges, P.W. (2008). Does cycling effect motor coordination of the leg during running in elite triathletes? *Journal of Science and Medicine in Sport,* 11, 371-380.

Chapman, A., Vicenzino, B., Blanch, P., Knox, J. and Hodges, P. (2004). Multidiscipline training demands may impair adaptation of the neuromuscular system in triathletes. 22nd International Symposium on Biomechanics in Sports, (Eds. Lamontagne, M. Robertson, D.G.E. and Sveistrup, H.), Ottawa, Canada, August 8th-12th.

Christiansen, C. L. (2008). The Effects of Hip and Ankle Stretching on Gait Function of Older People. *Archives of Physical Medicine and Rehabilitation,* 8, 1421-1428.

Chumanov, E.S., Wall-Scheffler, C. and Heiderscheit, B.C. (2008). Gender differences in walking and running on level and inclined surfaces. *Clinical Biomechanics*, 23, 1260-1268.

Connick, M.J. (2009). An investigation of movement frequencies: Implications for kinematics of running and gastrocnemius muscle response during cycling. Unpublished doctoral thesis. University of Birmingham.

Craib, M.W., Mitchell, V.A., Fields, K.B., Cooper, T.R., Hopewell, R., Morgan, D.W. (1996). The association between flexibility and running economy in sub-elite male distance runners. *Medicine and Science in Sports and Exercise,* 28, 737-743.

Dallam, G.M., Wilber, R.L., Jadelis, K., Fletcher, G. and Romanov, N. (2005). Effect of a global alteration of running technique on kinematics and economy. *Journal of Sports Sciences,* 23, 757-764.

Derrick, T.R., Dereu, D. And McLean, S.P. (2002). Impacts and kinematic adjustments during an exhaustive run*. Medicine & Science in Sports & Exercise,* 34, 998-1002.

DiBenedetto, M., Innes, K.E., Taylor, A.G., Rodeheaver, P.F., Boxer, J.A., Wright, H.J. and Kerrigan, D.C. (2005). Effect of a Gentle Iyengar Yoga Program on Gait in the Elderly: An Exploratory Study. *Archives of Physical Medicine and Rehabilitation,* 9, 1830-1837.

Dicharry, J. (2010). Kinematics and kinetics of gait: from lab to clinic. *Clinics in Sports Medicine,* 29, 347-364.

Dierks, T.A., Davis, I.S. and Hamill, J. (2010). The effects of running in an exerted state on lower extremity kinematics. *Journal of Biomechanics,* 43, 2993-2998.

Dillman, C. (1974). Kinematic analysis of running. *Exercise and Sports Science Reviews,* 3, 193-218.

Diss, C. (2001). The reliability of kinetic and kinematic variables used to analyse normal running gait. *Gait and Posture,* 14, 96-103.

Farley, C.T. and Ferris, D.P. (1998). Biomechanics of walking and running: centre of mass movements to muscle action. *Exercise and Sport Science Reviews,* 26, 253-285.

Fellin, R.E. and Davis, I.S. (2009). Comparison of warm-up periods for treadmill running. In: *Proceedings of the American Society of Biomechanics.* State College, PA, USA.

Ferber, R., McClay Davis, I. and Williams III, D.S. (2003). Gender differences in lower extremity mechanics during running. *Clinical Biomechanics*, 18, 350-357.

Franz, J.R., Paylo, K.W., Dicharry, J., Riley, P.O. and Kerrrigan, D.C. (2009). Changes in the coordination of hip and pelvis kinematics with mode of locomotion. *Gait and Posture,* 29, 494-498.

Gleim, G.W., Stachenfeld, N.S., Nicholas, J.A. (1990). The influence of flexibility on the economy of walking and jogging. *Journal of Orthopaedic Research,* 8, 814–823.

Godges, J.J., MacRae, H., Longdon, C., Tinberg, C. and MacRae, P. (1989). The effects of two stretching procedures on hip range of motion and gait economy. *Journal of Orthopaedic and Sports Physical Therapy,* 10, 350-357.

Gottshcall, J. S. and Palmer, B.M. (2000). Acute Effects of Cycling on Running Step Length and Step Frequency. *Journal of Strength and Conditioning Research,* 14, 97-101.

Gulbin, J. P. and Gaffney, P. T. (1999). Ultraendurance triathlon participation: typical race preparation of lower level triathletes. *Journal of Sports Medicine and Physical Fitness,* 39, 12-15.

Hardin, E.C., Van Den Bogert, A.J. and Hamill, J. (2004). Kinematic adaptations during running: Effects of footwear, surface and duration. *Medicine and Science in Sports and Exercise,* 36, 838-844.

Hausswirth, C. and Brisswalter, J. (2008). Strategies for improving performance in long distance duration events: Olympic distance triathlon. *Sports Medicine,* 38, 881-891.

Hausswirth, C. Bigard, A.X. and Guezenennec, C.Y. (1997). Relationships between running mechanics and energy cost of running at the end of a triathlon and a marathon. *International Journal of Sports Medicine,* 18, 330-339.

Heiden, T. and Burnett, A. (2003). The effect of cycling on muscle activation in the running leg of an Olympic distance triathlon. Sports Biomechaincs, 2, 35-49.

Heiderscheit, B. C., Chumanov, E. S., Michalski, M.P., Wille, C.M. and Ryan, M.B. (2011). Effects of step rate manipulation on joint mechanics during running. *Medicine and Science in Sport and Exercise*, 43, 296-302.

Herzog, W., Guimaraes, M. P., Strasser, P., Herzog, M. and Small, J. V. (1991). Moment-length relations of rectus femoris muscles of speed skaters/cyclists and runners. *Medicine and Science in Sports and Exercise*, 23, 1289-1296.

Hinnerichs, K.R., Conley, D.S., Evetovich, T.K., Engebresten, B.J. and Todd, J.B. (2004). Effects of Menstrual Cycle Phase and Oral Contraceptives on Muscular Strength, Endurance, and Flexibility. *Medicine & Science in Sports & Exercise,* 36, S35.

Hue, O., Le Gallais, D., Chollet, D., Bousanna, A. Prefaut, C. (1998). The influence of prior cycling on biomechanical and cardiorespiratory response profiles during running in triathletes. *European Journal of Applied Physiology and Occupational Physiology,* 77, 98-105.

Jones, A.M. (1998). A five year physiological case study of an Olympic runner. *British Journal of Sports Medicine,* 32, 39-43.

Kaneko, M., Matsumoto, M., Ito, A. and Fuchimoto, T. (1987). Optimal step frequency in constant speed running. In International Series on Biomechanics XIb (Ed by Jonsson), 803-807. Champaign, Illinois: Human Kinetics.

Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, 9,718-727.

Kerrigan, D.C., Todd, M.K. and Croce, U. (1998). Gender differences in joint biomechanics during walking: normative study in young adults. *American Journal of Physical Medicine and Rehabilitation,* 77, 2-7.

Kinugasa, T., Cerin, E. and Hooper, S. (2004). Single-subject research designs for assessing elite athletes' conditioning. *Sports Medicine,* 34, 1035-1050.

Laroche, D., Duval, A., Morisset, C., Beis, J-N., d'Athis, P., Maillefert, J-F. and Ornetti, P. (2011). Test-retest reliability of 3D kinematic gait variables in hip osteoarthritis patients. *Osteoarthritis and Cartilage,* 19, 194-199.

Lavcanska, V., Taylor, N.F. and Schache, A.G. (2005). Familiarization to treadmill running in young unimpaired adults. *Human Movement Science,* 24, 544-557.

Li, Y., Wang, W., Crompton, R.H. and Gunther, M.M. (2001). Free vertical moments and transverse forces in human walking and their role in relation to arm-swing. *Journal of Experimental Biology,* 204, 47-58.

Livingston, L.A. (1998). The quadriceps angle: a review of the literature. *Journal of Orthopaedic and Sports Physical Therapy*, 28, 105-109.

Malinzak, R.A. Colby, S.M., Kirkendall, D.T., Yu, B. and Garrett, W.E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clinical Biomechanics*, 16, 438-445.

Mann, R.A. and Hagy, J. (1980). Biomechanics of walking, running, and sprinting. *American Journal of Sports Medicine,* 8, 345-350.

Midgley, A.W., McNaughton, L.R. and Jones, A.M. (2007). Training to enhance the physiological determinants of long-distance running performance: Can valid recommendations be given to runners and coaches based on current scientific knowledge? *Sports Medicine,* 37, 857-880.

Millet, G. P. and Bentley, D. J. (2004). The physiological responses to running after cycling in elite junior and senior triathletes. *International Journal of Sports Medicine,* 25, 191-197.

Millet, G.P., Candau, R.B., Barbier, B., Busso, T., Rouillon, J.D. and Chatard, J.C. (2002). Modelling the transfers of training effects on performance in elite triathletes. *International Journal of Sports Medicine,* 23, 55-63.

Millet, G.P., Millet, G.Y. and Candau, R.B. (2001). Duration and seriousness of running mechanics alterations after maximal cycling in triathletes. Influence of performance level. *Journal of Sports Medicine and Physical Fitness*, 41, 147-153.

Millet, G.P. and Vleck, V. (2000). Physiological and biomechanical adaptations to the cycle to run transitions in Olympic triathlon: a review and practical recommendations for training. *British Journal of Sports Medicine*, 34, 384-390.

Mizrahi, J., Verbitsky, O., Isakov, E. and Daily, D. (2000). Effect of fatigue on leg kinematics and impact acceleration in long distance running. *Human Movement Science,* 19, 139-151.

Morton RH. (1997). Modelling training and overtraining, *Journal of Sports Science,* 15, 335-340.

Nicol, C., Komi, P.V. and Marconnet, P. (1991). Fatigue effects of marathon running on neuromuscular performance. *Scandanavian Journal of Medicine and Science in Sports*, 1, 10-17.

Novacheck, T.F. (1998). The biomechanics of running. *Gait and Posture,* 7, 77-95.

O'Connor, C.M., Thorpe, S.K., O,Malley, M.J. and Vaughan, C.L. (2007). Automatic detection of gait events using kinematic data. *Gait and Posture,* 25, 469-474.

O'Toole, M. L. (1989). Training for ultraendurance triathlons. *Medicine and Science in Sports and Exercise,* 21 (Supplement), S209-213.

Paavolainen, L.M., Nummela, A.T., and Rusko, H,K. (1999). Neuromuscular characteristics and muscle power as determinants of 5-km running performance. *Medicine and Science in Sport and Exercise,* 31, 124-130.

Palazzetti. S.,Margaritis I., Guezennec, C.Y. (2005). Swimming and Cycling Overloaded Training in Triathlon has no Effect on Running Kinematics and Economy. *International Journal of Sports Medicine,* 26, 193-199.

Petray, C.K. and Krahenbuhl, G.S. (1985). Running training, instruction in technique and running economy in 10 year old boys. *Research Quarterly for Exercise and Sport*, 56, 251-255.

Pohl, M.B., Lloyd, C. and Ferber, R. (2010). Can the reliability of three-dimensional running kinematics be improved using functional joint methodology? *Gait and Posture*, 32, 559-563.

Potter, J.J., Sauer, J.L., Weisshaar, C.L., Thelen, D.G. and Ploeg, H-L. (2008). Gender differences in bicycle saddle pressure distribution during seated cycling. *Medicine and Science in Sport and Exercise*, 40, 1126-1134.

Riley, P.O. (2008). A kinematics and kinetic comparison of overground and treadmill running. *Medicine and Science in Sport and Exercise*, 40, 1093-1100.

Saito, M., Kobayashi, K., Miyashita, M. and Hoshikawa, T. (1974). Temporal patterns in in running. In Medicine and Sport, Biomechanics IV. Eds R.C. Nelson and C. Morehouse. 106-111. University Park Press, Baltimore, Maryland.

Sandell, J., Palmgren, P.J. and Björndahl, L. (2008). Effect of chiropractic treatment on hip extension ability and running velocity among young male running athletes. *Journal of Chiropractic Medicine,* 7, 39-47.

Sauer, J.L., Potter, J.J., Weisshaar, C.L., Ploeg, H-L., and Thelen, D.G. (2007). Influence of gender, power and hand position on pelvic motion during seated cycling. *Medicine and Science in Sport and Exercise*, 39, 2204-2211.

Saunders, P.U., Pyne, D.B., Telford, R.D. and Hawley, J.A. (2004). Factors affecting running economy in trained distance runners. *Sports Medicine*, 34, 465-485.

Savelberg, H. H. and Meijer, K. (2003). Contribution of mono- and biarticular muscles to extending knee joint moments in runners and cyclists. *Journal of Applied Physiology,* 94, 2241-2248.

Schache, A.G., Blanch, P., Rath, D., Wrigley, T. and Bennell, K. (2003). Differences between the sexes in the three-dimensional angular rotations of the lumbo-pelvic-hip complex during treadmill running. *Journal of Sport Sciences*, 21, 105-118.

Schache. A.G., Fregly, B. J., Crossely, K.M., Hinman, R.S and Pandy, M.G. (2002). The effect of gait modification on the external knee adduction moment is reference frame dependent. *Clinical Biomechanics,* 23, 601-608.

Schache, A. G., Blanch, P. D., Rath, D. A., Wrigley, T. V., Starr, R. and Bennell, K.L. (2001). A comparison of overground and treadmill running for measuring the three-dimensional kinematics of the lumbo-pelvic-hip complex. *Clinical Biomechanics,* 16, 667-680.

Schache, A.G., Blanch, P.D. and Murphy, A.T. (2000). Relation of anterior pelvic tilt during running to clinical and kinematic measures of hip extension. *British Journal of Sports Medicine,* 34, 279-283.

Schache, A. G., Bennell, K. L., Blanch, P. D. and Wrigley, T. V. (1999). The coordinated movement of the lumbo-pelvic-hip complex during running: a literature review. *Gait and Posture,* 10, 30-47.

Simoneau, G.G., Hoenig, K.J., Lepley, J.E. and Papnek, P.E. (1998). Influence of hip position and gender on active hip internal and external rotation. *Journal of Orthopaedic and Sports Physical Therapy,* 28, 158-164.

Slawinski, J.S. and Billat, V.L. (2004). Difference in Mechanical and Energy Cost between Highly, Well, and Nontrained Runners. *Medicine and Science in Sports and Exercise,* 36, 1440-1446.

Smith, D.J. (2003). A framework for understanding the training process leading to elite performance. *Sports Medicine,* 33, 1103-1126.

Tew, G.A. (2005). The effect of cycling cadence on subsequent 10km running performance in well-trained triathletes. *Journal of Sports Science and Medicine*, 4, 342-353.

Thordason, D.B. (1997). Running biomechanics, *Clinical Sports Medicine*, 16, 239-247.

Tseh, W.C., Caputo, J.L. and Morgan, D.W. (2008). Influence of gait manipulation on running economy in female distance runners. *Journal of Sports Science and Medicine,* 7, 91-95.

Vleck, V. E., Bentley, D. J., Millet, G. P. and Burgi, A. (2008). Pacing during an elite Olympic distance triathlon: comparison between male and female competitors. *Journal of Science and Medicine in Sport*, 11, 424-432.

Wall, J.C. and Charteris, J. (1981). A kinematic study of long-term habituation to treadmill walking. *Ergonomics,* 24, 531-542.

Watt, J.R., Jackson, K., Franz, J.R., Dicharry, J., Della Croce, U. and Kerrigan D.C. (2009). Effect of a supervised hip flexor-stretching program on gait in healthy elders. *Gait and Posture*, 30, S36-S37.

Weyand, P.G., Sternlight, D.B., Bellizzi, M.J. and Wright, S. (2000). Faster top running speeds are achieved with greater ground reaction forces not more rapid leg movements. *Journal of Applied Physiology,* 89, 1991-1999.

Williams, K.R. and Cavanagh, P.R. (1987). Relationship between distance running mechanics, running economy and performance. *Journal of Applied Physiology,* 63, 1236-1245.

Williams, K.R., Cavanagh, P.R. and Ziff, J.L. (1987). Biomechanical studies of elite female distance runners. *International Journal of Sports Medicine*, 8(suppl.), 107-118.

Wilson, C., Simpson, S., Hamill, J., (2009). Movement coordination patterns in triple jump training drills. *Journal of Sports Sciences*, 27, 277-282.

Winters, M.V., Blake, C.G., Trost, J.S., Marcello-Brinker, T.B., Lowe, L., Garber, M.B. and Wainner, R.S. (2004). Passive versus active stretching of hip flexor muscles in subjects with limited hip extension: A randomized clinical trial. *Physical Therapy,* 84, 800-807