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Concurrent training: the acute effects of intensity, sequence and frequency of strength and endurance training on running performance

Thesis submitted by

Kenji DOMA BSpExSc (Hons)

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for the degree of Doctor of Philosophy

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Declaration on ethics

The studies as part of this doctoral degree were conducted in accordance with the research ethics guidelines of the *WORLD MEDICAL ASSOCIATION DECLERATION OF HELINSKI – Ethical Principles for Medical Research Involving Human Subjects* (2008), the *Joint NHMRC/AVCC Statement and Guidelines on Research Practice* (1997) and the *James Cook University Statement and Guidelines on Research Practice* (2001). The research methodology and protocols of each study in the thesis received clearance from the James Cook University Experimentation Ethics Review Committee (H3536).

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Abstract

Introduction: Numerous studies have shown that the combination of strength and endurance training (i.e. concurrent training) induces sub-optimal strength and/or endurance adaptations. However, the investigation of the acute effects of strength training on endurance performance is limited. Study 1 examined the effects of intensity– and volume– (i.e. whole body versus lower body only) of strength training with slow eccentric contractions on running economy (RE) (i.e. below anaerobic threshold [AT]) and time-to-exhaustion (TTE) (i.e. above AT) 6 hours post. The purpose of Study 2 was twofold. First, to examine RE during a two-stage incremental protocol that was combined into an endurance training session 6 hours following a strength training session. Second, to examine RE and TTE the day after strength and endurance training sessions have been undertaken on the same day. Study 3 examined the acute effects of the sequence of strength and endurance training on RE, TTE the following day. Study 4 examined the accumulation effects of combining consecutive-day endurance training with alternating-day strength training on RE and TTE over a 6-day period.

Methods: For Study 1, fifteen trained and moderately endurance trained male runners undertook high intensity whole body (HW), high intensity lower body only (HL) and low intensity whole body (LW) strength training sessions with fast concentric (one second) and slow eccentric (four seconds) contractions in random order. Six hours following each strength training session, a RE test with TTE was conducted to collect cost of running (C_R) and rating of perceived exertion (RPE). For Study 2, twelve trained and moderately trained male runners performed strength and endurance training sessions 6 hours apart with a running performance test conducted the following day. The C_R and RPE were collected during the endurance training session whereas C_R, RPE and TTE were collected during the running performance

test. For Study 3, fourteen trained and moderately trained runners performed strength training prior to running sessions (SR) and a running prior to strength training sessions (RS) in randomized order. The strength training and running sessions were performed 6 hours apart. The day following the SR– and RS sequences, a RE test was conducted to collect C_R, RPE and TTE. For Study 4, 16 male and 8 female moderately trained runners were randomly allocated into a concurrent training (CON) group or a strength training (ST) group. The CON group undertook strength training sessions on alternating days in conjunction with endurance training sessions on consecutive days over a 6-day period. The strength and endurance training sessions were separated by 9 hours on the first, third and fifth day. One week later, the experimental group performed endurance training sessions for three consecutive days for control purposes. The C_R, RPE and TTE were collected during the endurance training sessions. For Chapter 9, knee extensor torque was measured prior to the strength and endurance training sessions. The strength training exercises in Chapter 7, 8, and 9 were performed at a self-selected pace.

Results: In Study 1, HW, HL and LW sessions had no effect on RE and the LW session had no effect on TTE ($P \geq 0.05$). However, HW and HL sessions significantly reduced TTE ($P < 0.05$). For Study 2, C_R significantly increased during the second stage of the endurance training session ($P < 0.05$). However, during the running performance test, C_R and RPE were significantly increased whereas TTE was significantly decreased ($P < 0.05$). In Study 3, C_R and RPE significantly increased during SR-RE ($P < 0.05$) although no significant differences were found during RS-RE ($P \geq 0.05$). Time to exhaustion was significantly reduced during SR-RE and RS-RE ($P < 0.05$). In Study 4, the CON group showed a significant reduction in TTE during the experimental days ($P < 0.05$) although no differences were found during the control days ($P \geq 0.05$). Torque was significantly reduced during the experimental days ($P <$

0.05). No significant differences were found in C_R and RPE between the endurance training sessions ($P \geq 0.05$). No significant differences were found in torque for the ST group and during the control days for the CON group ($P \geq 0.05$).

Conclusion: According to Study 1, a 6 hour recovery period following HW, HL and LW sessions with slow eccentric contractions does not attenuate running performance below AT although affected above AT for trained and moderately trained runners. For Study 2, the findings showed that RE is impaired 6 hours following a strength training session performed at a self-selected pace. Furthermore, strength and endurance training performed on the same day appears to impair running performance the following day. For Study 3, SR-sequence impaired both sub-maximal running performance (i.e. RE) and running performance at maximum effort (i.e. TTE) compared to the RS-sequence which only affected running performance at maximum effort the following day. Subsequently, the accumulation of fatigue appears to be greater during the SR- compared to the RS-sequence. For Study 4, running performance at maximum effort is impaired and torque is consistently reduced with a concomitant increase in rating of muscle –soreness and –fatigue when combining alternating-day strength training with consecutive-day high intensity endurance training.

Practical applications: The attenuation in running performance suggests that strength training may compromise the quality of endurance training sessions. In order to minimize potential fatigue during concurrent training, the following recommendations can be given for trained and moderately trained runners:

1. when combining a high– or low– intensity strength training session using slow eccentric contractions with a low to moderate intensity running session, at least a 6-

hour recovery period between each mode of training session should be provided, however;

2. at least a 9-hour recovery period is needed with high intensity self-paced strength training;
3. perform moderate to high intensity endurance training sessions 6 hours prior to high intensity strength training sessions on the same day when undertaking low to moderate running sessions the following day;
4. prescribe high intensity self-paced strength training sessions with high intensity running sessions on alternating days.

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AMPK	Adenosine monophosphate-activated protein kinase
A_{ROM}	Ankle range of motion
ATP	Adenosine tri-phosphate
Base-End	Endurance training session for baseline
Base-RE	Running economy test for baseline
CI	Confidence interval
CK	Creatine kinase
CON	Concurrent training group
CS	Cycling prior to strength training
CSA	Cross sectional area
CV	Coefficient of variation
DOMS	Delayed on-set of muscle soreness
EIMD	Exercise-induced muscle damage
EMG	Electromyography
END	Endurance training group
End	Running session
ES	Endurance training prior to strength training
FFM	Fat free mass
$H_{AB/AD}$	Hip abduction/adduction
HL	High intensity lower body only
H_{ROM}	Hip range of motion
HW	High intensity whole body
ICC	Intra-class correlation coefficient
KET	Knee extensor torque
KF_{AS}	Maximum knee flexion after foot strike
KF_S	Maximum knee flexion during swing phase

LL	Low intensity lower body only
LW	Low intensity whole body
MFGC	Muscle force generation capacity
MSE	Mean squared error
mTOR	Mammalian target of rapmyasin
MVC	Maximal voluntary contraction
MHC	Myosin heavy chain
P13K	Phosphoinositide-3 dependent kinase
PCr	Phosphocreatine
PGC-1α	Peroxisome proliferator-activated receptor gamma coactivator
PKB	Protein kinase B
PLV_{LF}	Lateral flexion of the pelvis
Post End	Physiological measures collected following the running session
Post RE	Physiological measures collected following the running economy test
Post St	Physiological measures collected following the strength training session
Post-RE test	Running economy test 24 hours post the strength session
Pre End	Physiological measures collected prior to the running session
Pre RE	Physiological measures collected prior to the running economy test
Pre St	Physiological measures collected prior to the strength training session
RE	Running economy
rLOA	Ratio limits of agreement
RMF	Rating of muscle fatigue
RMS	Rating of muscle soreness
RPE	Rating of perceived exertion
RS Sequence	Strength training session 6 hours following a running session
RS-RE	RE test conducted 24 hours following the running session for the RS sequence
SC	Strength training prior to cycling

S-Cyc	Strength and cycling endurance
SE	Strength training prior to endurance training
SR Sequence	Running session 6 hours following a strength training session
SR-RE	RE test conducted 24 hours following the strength training sessions for the SR sequence
S-Run	Strength and running endurance
ST	Strength training group
St	Strength training session
THX_{LF}	Lateral flexion of the thorax
TTE	Time-to-exhaustion
VO_2	Oxygen consumption
VO_{2max}	Maximal oxygen consumption
WD	Worthwhile differences

Chapter 1

1.1 Introduction

Incorporating strength and endurance training sessions in the one training regime irrespective of whether the training is performed on the same day or separate days is known as concurrent training (Hickson, 1980). The literature advises health professionals to prescribe strength and endurance exercises in the one training regime in order to improve and sustain health-related fitness (Garber et al., 2011). However, concurrent training may create complications from an athletic standpoint, since endurance training has predominantly been shown to inhibit strength adaptations (Leveritt & Abernethy, 1999). Such physiological incompatibility found with concurrent training is referred to as the "interference phenomenon" (Bell, Syrotuik, & Socha, 1997; Leveritt, Abernethy, Barry, & Logan, 1999).

Chronic and acute hypotheses have been proposed in an attempt to explain the negative effect that concurrent training has on strength performance. The acute hypothesis suggests that the residual fatigue experienced following endurance training reduces muscular contractility, and hence, impairs strength performance (Docherty & Sporer, 2000; Leveritt, et al., 1999). The chronic hypothesis states that the muscle cannot undergo optimal metabolic and morphological adaptations in response to concurrent training because the physiological adaptations induced by endurance training are vastly different and can be antagonistic to strength training (Docherty & Sporer, 2000). Additionally, the chronic interference may be attributed to the attenuation of muscular tension due to the accumulation of acute residual fatigue from preceding endurance exercise that limits the strength stimulus required for optimal strength development (Leveritt & Abernethy, 1999). In view of the antagonistic effects concurrent training has on physiological adaptations, it is imperative that studies are conducted in order to determine the compatibility of strength and endurance training by understanding the acute residual responses and the subsequent chronic adaptation of both modes of training.

Since the earliest work that has shown attenuation in the development of strength in response to concurrent training (Hickson, 1980), the literature has produced an array of findings. Whilst numerous studies have shown impaired endurance adaptations (Bell, Petersen, Wessel, Bagnall, & Quinney, 1991; Glowacki et al., 2004) a greater number of concurrent training studies have shown attenuation in strength development (Gergley, 2009; Izquierdo, Häkkinen, Ibanez, Kraemer, & Gorostiaga, 2005). It is also worth mentioning that some studies have shown no antagonistic effects on strength (McCarthy, Pozniak, & Agre, 2002; Sillanpää et al., 2008) or endurance adaptations (Häkkinen, Hannonen, Nyman, Lyyski, & Häkkinen, 2003; Mikkola, Rusko, Nummela, Pollari, & Häkkinen, 2007; Millet, Jaouen, Borrani, & Candau, 2002) following concurrent training.

The discrepancies in findings for concurrent training may be due to differences in the study design and/or training protocols (Leveritt, Abernethy, Barry, & Logan, 2003). These include the mode of endurance exercise, variation in the intensity and volume of strength and endurance training, the sequence of strength and endurance training sessions, the recovery period between strength and endurance training sessions and the frequency of training sessions per week. These variations in training methodology are important because the physiological adaptations that are induced following exercises are dependent on the type and degree of the stimulus applied during the training session (Baar, 2006) as well as the incorporation of recovery post training (Leveritt, et al., 1999). Therefore, identifying the mechanisms associated with the responses from a given selection of strength and endurance exercise would provide evidence for the type of adaptation induced. However, most studies on concurrent training have examined chronic strength and endurance adaptations whilst the investigation of the acute effects has been limited. The few studies that have examined the acute effects of concurrent training have mostly incorporated endurance exercises prior to strength exercises in order to determine the effects of endurance training on subsequent strength performance (Bentley, Smith, Davie, & Zhou, 2000; Bentley, Zhou, & Davie, 1998; Millet, Martin, Lattier, & Ballay, 2003). Consequently, there is limited information available regarding the acute effects that prior strength training has on endurance performance.

In one of the few studies to investigate the effects of strength training on endurance performance, Palmer and Sleivert (2001) reported that running economy (RE) was impaired 8 hours following strength training. However, the RE protocol was limited to a single running speed and only one type of strength training protocol was incorporated. Deakin (2004) examined the impact of high intensity whole body (HW), high intensity lower body only (HL) and low intensity lower body (LL) only strength training on sub-maximal cycling performance three hours post. The author showed a higher physiological cost for cycling performance following high intensity compared to low intensity strength training. Furthermore, whole body strength training showed a greater physiological cost than lower body only strength training.

The findings by Deakin (2004) suggest that alteration in strength training –intensity and –volume can impact on subsequent endurance performance. However, the endurance performance protocol was limited to cycling. Given that the physiological responses vary between cycling and running (Millet, Vleck, & Bentley, 2009) and that neural recruitment patterns differ according to running speed (Abernethy, Thayer, & Taylor, 1990), the question then is, would various strength training methods affect running performance at varying running speeds? Furthermore, Palmer et al (2001) and Deakin (2004) have confirmed possible detrimental effects that strength training may have on endurance performance. Acute studies thus far have not examined methods of limiting the attenuation of endurance performance following strength training. This could be accomplished by reducing the speed of eccentric contractions, given that fast– compared to slow eccentric contractions have shown to cause greater muscle –damage and –fatigue (Chapman, Newton, Sacco, & Nosaka, 2006). Chapman et al (2008) reported increased excess post exercise oxygen consumption (EPOC) 24 hours following strength training performed with fast concentric (i.e. one second) and slow eccentric (i.e. four seconds) contractions. However, Chapman and colleagues (2008) did not examine the effect of altering the intensity and volume of strength training with slow eccentric contractions and the physiological measures were collected at rest. The effects of systematically varying strength training intensity and volume with fast concentric and slow eccentric contractions on running performance several hours post, at various running speeds, has not been examined. Such an investigation would enhance the understanding of the acute sensitivity that strength training has on endurance performance when manipulating training variables.

Whilst there are a number of studies that have examined the acute effects of endurance training on strength training performance (Bentley, et al., 2000; Bentley, et al., 1998; Millet, et al., 2003) and strength training on endurance performance (Deakin, 2004; Palmer & Sleivert, 2001), there is limited investigation on the acute effects of altering the sequence of strength and endurance training. The few studies that have examined the sequence of the mode of training have examined chronic adaptations over a period of weeks (Chtara et al., 2008; Gravelle & Blessing, 2000; Silvers & Dolny, 2011). The earliest study examining the effects of altering the sequence between strength and endurance exercises within a concurrent training program was conducted by Collins and Snow (1993). The participants in this study were allocated into groups that performed strength only (ST), endurance only (END), strength followed by endurance training (SE) and endurance followed by strength training (ES). The results showed no difference in one repetition maximum (1RM) and maximal oxygen consumption (VO_{2max}) between SE and ES groups. It was concluded that strength and endurance adaptations were independent to the sequence of the mode of training. However, recent findings by Gravelle and Blessing (2000), Chtara et al (2005) and Chtara et al (2008) showed a significant difference in VO_{2max} and 4 km running time trial performance although no significant differences were shown in 1RM between SE and ES groups following 11-12 weeks of concurrent training. Although Collins and Snow (1993) showed no difference in either strength nor endurance adaptations between SE and ES groups, other studies (Chtara, et al., 2005; Gravelle & Blessing, 2000) have shown that endurance adaptation was affected as a result of the sequence of the mode of training.

If endurance adaptations are affected by the sequence of strength and endurance exercises, do the acute responses throughout the training program reflect these changes? A study carried out by Drummond and colleagues (2005) examined the acute responses of aerobic and resistance exercise sequence and showed that EPOC was greater when running preceded strength training compared to when strength preceded running. However, the acute effects of training sequence were limited to metabolic measures at rest and the endurance performance measures were unknown. Deakin (2004) examined sub-maximal cycling performance in response to the acute residual effects of altering the sequence of strength training and cycling. The results showed that the physiological cost of cycling was greater when strength training preceded endurance training although unaffected with the reverse sequence. However, running performance measures were not collected and performance measures were limited to physiological responses on the same day. Given that acute responses from a single strength training session have been shown to alter running gait patterns on the same day (Kellis & Liassou, 2009; Paschalis et al., 2007), a combination of strength and endurance training with alterations in their sequences on the same day may cause changes to running kinematics the following day. To date, however, the impact of the sequence of the mode of training on running –performance and –kinematics the following day have not been examined and are aspects of concurrent training that require further research. Such an investigation would demonstrate how the body responds to strength and endurance training sequence over consecutive days which may be useful to explain mechanisms associated with concurrent training adaptation.

When performing strength and endurance training, a process of transient increase and inhibition of physiological phenomena occurs during and following every training session and when repeated over a number of weeks, manifests a specific form of adaptation (Hawley, 2009). Thus, examining the acute effects of strength and endurance training would shed light on the link between the acute responses and subsequent adaptations. However, the studies that have examined the acute effects of strength and endurance training have been limited to a single training session (Bentley, et al., 2000; Palmer & Sleivert, 2001; Twist & Eston, 2005) or to two training sessions on the same day (Deakin, 2004; Drummond et al., 2000). In order to determine the mechanisms of training adaptation induced and the possible recurring interference in concurrent training, it is essential to systematically examine numerous strength and endurance training sessions during a particular component of a concurrent training program over several days (e.g. a microcycle). Indeed, it has been recommended that beginners and intermediate weight lifters perform strength training sessions two to four times per week (i.e. at least 48 hours of recovery between training sessions) to optimise strength-, power- and strength endurance- adaptations (Kraemer et al., 2002) whereas moderate to high intensity endurance training sessions are commonly prescribed on a daily basis for trained and moderately trained individuals (Faude, Meyer, Urhausen, & Kindermann, 2009). Collectively, would fatigue accumulate over a micro-cycle of a concurrent training program if alternating-day strength training is performed in conjunction with consecutive-day endurance training? To date, such an investigation has not been conducted.

1.2 Statement of the Problem

To date, studies of the acute physiological responses to concurrent training have predominantly examined strength training performance following endurance exercises with limited investigations of the effects strength training exercises have on endurance performance. Studies that have investigated the acute effects of strength training on endurance performance have been limited to a single type of strength training protocol or to cycling performance. Subsequently, the influence that various strength training methodologies (e.g. high versus low, whole body versus lower body only, slow eccentric contraction velocities) have on other types of endurance exercises, such as running, is unknown.

Secondly, most studies investigating the response of altering the sequence of strength and endurance training have examined chronic adaptations following concurrent training. The one study that did examine the acute response by altering the sequence of the mode of training used cycling as an endurance training and performance protocol. Furthermore, the examination of acute responses following strength and endurance training has been limited to physiological measures. In addition, changes in biomechanics as a factor for the impairment of endurance performance have not yet been investigated.

Finally, the majority of the concurrent training studies thus far have focused on the physiological adaptations induced after a given training program. Furthermore, the acute concurrent training studies that have been undertaken have been limited to examining strength and endurance training sessions in a single day. The acute effects of alternating-day strength training with consecutive-day endurance training on running performance have not yet been examined.

1.3 Aims of the Project

The project was separated into four studies with the following aims:

1. to examine the acute residual physiological effects of different intensities (high versus low) and volume (whole body versus lower body only) of strength training exercises with slow eccentric contractions on running performance 6 hours post;
2. to examine the effect of strength training using self-selected contraction velocities
    a. on running –performance and –kinematics 6 hours post;
    b. combining with endurance training, 6 hours apart, and its effect of on running –performance and –kinematics the following day;
3. to examine the influence of the sequence of strength training using self-selected contraction velocities and endurance training performed on the same day, 6 hours apart, and its effect on running –performance and –kinematics the following day; and
4. to examine the effect of performing strength training using self-selected contraction velocities on alternating days and endurance training on consecutive days on running performance over a 6-day period.

1.4 Hypotheses

It was hypothesised that:

1. strength training with slow eccentric contractions would not affect running performance 6 hours post regardless of variation in strength training methodology (i.e. intensity or volume);
2. strength training using self-selected contraction velocities;

    a. would impair running performance and alter kinematics 6 hours post;
    b. combined with endurance training, despite a 6 hour recovery period, would impair running performance and alter running kinematics the following day;
3. performing strength training using self-selected contraction velocities prior to endurance training, despite a 6 hour recovery period, would impair running performance and alter running kinematics the following day. However, the reverse sequence would not impair running performance or alter running kinematics the following day; and
4. performing strength training (i.e. self-selected contraction velocities) on alternating days and endurance training on consecutive days would impair running performance on a daily basis.

1.5 Significance of the Study

The series of studies will enhance the understanding of the compatibility of strength and endurance training from an acute perspective. For Chapters 6, 7 and 8, concurrent training programs could be produced in order to minimise the “interference phenomenon” whilst maximising endurance adaptations. This could be accomplished by 1) understanding the effect that the intensity and volume of strength training sessions with slow eccentric contractions has on running performance, 2) understanding the effect that the sequence of the mode of training has on running performance, 3) analysing running kinematics which will provide additional information that may explain the mechanisms responsible for changes in running performance as a result of preceding strength and/or endurance training. Chapter 9 is significant because it will complement the above points by demonstrating the relationship between the day-to-day acute physiological responses following strength and endurance training sessions. Collectively, the findings from the above studies will give coaches information necessary to make adjustments to training programs in order to optimise training stimuli and recovery dynamics and thus maximise training adaptation. In addition, furthering the understanding of the “interference phenomenon” from an acute perspective may enhance the coaches’ ability to monitor their athletes during concurrent training and reduce the prevalence of injuries.

1.6 Delimitations

The current studies were delimited to:

1. trained middle to long distance runners (1500-10,000 m) who were covering at least 50 $km.week^{-1}$ and moderately trained field-based endurance athletes with various sporting backgrounds (e.g. basketball, cricket and soccer) covering 5-10 $km.week^{-1}$. Therefore, the findings may not be extrapolated to other population groups (i.e. sedentary or non-endurance athletes); and
2. athletes who are not resistance training; and
3. running performance variables. The extrapolation of the findings to other endurance parameters (e.g. cycling, rowing and swimming) may not be applicable;
4. a number of strength training exercises (i.e. bench press, bench pulls, incline leg press, leg curls and leg extension). The effect of strength training on running performance may not be the same following other strength training exercises; and
5. knee extensor muscle groups for strength indices. Therefore, the extrapolation of the findings to other muscle groups regarding strength indices may not be applicable.

1.7 Limitations

The findings of the current studies were limited by the:

1. volunteers who were not a random sample of the endurance training community; and
2. volunteers with minimum experience in resistance training in order to homogenise the sample; and
3. sample size was limited to accessibility of participants whom met the recruitment criteria during the course of the studies, however, sample size calculations were conducted to justify the sample sizes; and
4. standard technical and biological variability. Every effort was made to control for such fluctuations by calibrating all equipment, requiring participants to wear the same shoes, conducting tests at the same time of the day on the same day/time of the week and controlling training volume and food intake.

1.8 Format of the thesis

The first chapter of this thesis provides a brief introduction of concurrent training and general issues associated with combining strength and endurance training in the one training regime. The second chapter reviews the literature of concurrent training with further in-depth analyses of prior studies on the chronic and acute effects of strength and endurance training. The Chapters 3, 4 and 5 report the reliability of the physiological (Chapter 3) and biomechanical (Chapter 4) components of the running performance test and the maximal voluntary contraction test (Chapter 5) that were used during the four studies (Chapters 6, 7, 8 and 9, respectively) conducted as part of this thesis. Chapters 3 and 4 were written as journal articles and have been accepted for publication. Chapter 5 is substantially shorter since the analyses were limited to a single performance variable. Subsequently, the paper has not been written for publication purposes. Nonetheless, Chapter 5 has been structured in the format of a scientific paper with an introduction, methods, results, discussion and conclusion.

The four studies that make up Chapters 6, 7, 8 and 9, respectively, were conducted to ensure logical progressions from one study to the next. This was made possible by generating pertinent scientific questions and hypotheses according to the key issues identified from previous literature. Furthermore, the methodology of each study was constructed based on findings obtained by the previous research of this thesis. A brief paragraph has been included prior to the introduction in Chapters 7, 8 and 9 to explain the contribution that the previous research had in constructing the following study. The study in Chapter 6 examined the acute effects of intensity– and volume– of strength training on running performance. The study in Chapter 7 examined the effects of combined strength and endurance training on running performance the following day. The study in Chapter 8 examined the acute effects of the sequence of strength and endurance training on running performance the following day. The study in Chapter 9 examined the cumulative effects of strength and endurance training on running performance over a 6-day period.

Chapter 10 summarizes the key findings between the four studies (Chapter 6, 7, 8 and 9, respectively), provides the practicality of each finding, explains possible avenues for future research and concludes with a brief paragraph of the key points addressed throughout this thesis. Chapters 6, 7 and 8 have been accepted for publication and the Chapter 9 is currently under review by a peer-reviewed journal.

Chapter 2

2.1. Physiological Compatibility of Strength and Endurance Training

The incorporation of strength and endurance training sessions in the one training program is known as concurrent training (Leveritt & Abernethy, 1999). The physiological adaptations induced by strength and endurance training, however, are vastly different and sometimes antagonistic. Studies have empirically shown that one mode of training is more effective in inducing physiological adaptations than when both modes of exercises are performed concurrently (Bell, Syrotuik, Martin, Burnham, & Quinney, 2000; Dolezal & Potteiger, 1998; Gergley, 2009; Glowacki, et al., 2004). Most notably, concurrent training appears to interfere with strength training adaptation to a greater degree than endurance training adaptation (Leveritt, et al., 1999). Nonetheless, scientific articles still advise coaches and health professionals to prescribe strength and endurance exercises simultaneously in a training program to enhance athletic performance (Balabinis, Psarakis, Moukas, Vassiliou, & Behrakis, 2003; Gergley, 2009) and improve health-related fitness (Garber, et al., 2011). Subsequently, conducting research to understand the compatibility between the two modes of exercise would benefit sport and health-related practice. For example, ascertaining the degree of interference in training adaptation as a result of combining strength and endurance training could accelerate recovery during rehabilitation in a clinical setting. In science, determining the mechanisms of the physiological antagonisms during and following concurrent training may allow exercise professionals to structure programs that would minimize interference in training adaptation and optimize performance (Davis, Wood, Andrews, Elkind, & Davis, 2008a; Sale, Jacobs, & Garner, 1990).

2.2. Interference in Strength Development with Concurrent Training

A vast number of concurrent training studies have shown impaired strength development when strength and endurance exercises are combined simultaneously (Hawley, 2009). The work conducted by Hickson (1980) was one of the first to demonstrate attenuation of strength development as a result of concurrent training. Hickson (1980) examined the effects of combining strength and endurance training compared to adaptations induced when both modes of training were performed independently. The exercise groups were separated into ST and END groups and a concurrent strength and endurance training (CON) group that followed the same training regime as the ST and END groups simultaneously for ten weeks. The results showed that VO_{2max} increased by 25% and 20% for the END group and the CON groups, respectively. However, no differences were found for the ST group. Strength development was consistent throughout the training weeks for the ST group, but no notable increase in strength was found for the END group. The rate of strength development for the CON group was initially similar to that of the ST group, however, declined after 7 weeks. As the CON group trained both modes of exercises 5 $d \cdot wk^{-1}$, it was suggested that the sheer volume of training may have led to residual fatigue that could have attenuated strength development.

Similar to the study by Hickson (1980), recent concurrent training studies have also shown sub-optimal strength development (Bell, et al., 2000; Chtara, et al., 2008; Dolezal & Potteiger, 1998; Gergley, 2009; Putnam, Xu, Gillies, MacLean, & Bell, 2004). For example, Bell et al (2000) investigated the effect of concurrent strength and endurance training on muscular strength amongst ST–, END– and CON groups. The results showed that leg press and knee extension 1RM was significantly increased for the ST– and CON groups, however, the strength gains were greater for ST group compared to the CON group.

In light of the above-mentioned studies, it is apparent that concurrent training interferes with strength development. This attenuating effect of concurrent training on strength adaptations has been referred to in literature as the “interference phenomenon” (Docherty & Sporer, 2000). Several hypotheses have been postulated for the physiological interferences that occur in response to concurrent training. The acute hypothesis proposes that residual fatigue caused from the preceding endurance exercise compromises the ability of the muscle to develop tension (Craig, Lucas, & Pohlman, 1991). This subsequently decreases muscular contractility and therefore hinders strength training performance (Leveritt & Abernethy, 1999). The chronic hypothesis states that the skeletal muscle is placed in a state of physiological antagonism with concurrent training. For example, muscle fibre hypertrophy, muscle fibre type transformations, endogenous enzymatic activity, endocrine responses, muscle morphological structure and capillarization induced by endurance training are vastly different to adaptations by strength training (Abernethy, Jurimae, Logan, Taylor, & Thayer, 1994; Abernethy, et al., 1990). These physiological antagonisms in response to strength and endurance exercises may be causing the interference in adaptation when both modes of exercises are combined in the one training regime.

2.3. Chronic Mechanisms for the Interference of Strength Development

Although concurrent training has been shown to interfere with the development of strength and endurance adaptations, the attenuation in strength appears to be more consistent than endurance adaptations (Docherty & Sporer, 2000; Leveritt, et al., 1999). The physiological mechanisms contributing to the interference of adaptations with concurrent training is still a matter of debate. The accumulation of residual fatigue caused by endurance training from each training session may lead to impaired strength development. However, this acute effect of concurrent training and its impact on chronic adaptation is still under speculation due to the limitation of such investigation. Recent studies have reported that the genetic and molecular responses from strength and endurance training may bridge the gap between the acute responses and the subsequent physiological adaptation that is specific to the mode of exercise and explain the underlying physiological factors for the interference phenomenon (Baar, 2006; Hawley, 2009; Nader, 2006).

2.3.1. Genetic and Molecular Adaptation to Concurrent Training

Even though a single bout of exercise is insufficient in increasing strength and endurance qualities, cellular and molecular alterations that occur over the course of training can induce physiological adaptations in response to cumulative acute effects that is specific to the mode of exercise (e.g. hypertrophy, increased oxidative enzymes and mitochondrial density) (Baar, 2006). The mechanical stimulus produced during muscle contractions causes the initiation of primary and secondary messengers, which mediate the activation and/or suppression of signalling pathways and govern exercise-induced gene expression and protein synthesis (Coffey & Hawley, 2007). In response to exercise, there is a transient increase in messenger proteins undergoing adaptational changes to a new training threshold (Hawley, 2009). However, due to the shorter half-life of the message compared to the exercise-induced proteins, the transient increase in messenger ribonucleic acid has a more cumulative effect on the protein (Neufer & Dohm, 1993). Subsequently, the accumulation of enhanced exercise induced gene expression and protein synthesis following every training session enables an increased physiological capacity for adaptation (MacLean, Zheng, & Dohm, 2000).

After the performance of strength training, the acute response is primarily protein synthesis which occurs as a result of an increase in the degree of protein synthesis per molecule of ribonucleic acid (Smith, Palmer, & Reeds, 1983; Wong & Booth, 1988). The signalling pathways that regulate protein synthesis in response to resistance training are controlled by proteins such as phosphoinositide-3 dependent kinase (P13k), protein kinase B (PKB), the mammalian target of rapmyasin (mTOR) and the ribosomal protein S6 kinase 1 (Bolster et al., 2003; Hernandez, Fedele, & Farrell, 2000; Nader & Exxer, 2001). In particular, the P13k-PKB-mTOR cascade is regulated by effectors of ribosomal protein S6 kinase and eukaryotic initiation factor 4E. Ribosomal protein S6 kinase 1 has been shown to orchestrate the regulation of cell size and protein synthesis (Coffey & Hawley, 2007) with ribosomal protein S6 kinase playing an imperative role in muscle hypertrophy (Bodine et al., 2001; Terzis et al., 2008). Alternatively, the eukaryotic initiation factor 4E activity increases the activation of P13k-PKB-mTOR cascade, leading to an inhibition of the eukaryotic initiation factor 4E cap-binding protein (Bolster, et al., 2003). Collectively, the accumulation of protein synthetic reactions in response to muscular contractions over the course of a strength training program induces hypertrophic adaptations and contributes to developing muscular strength (Baar, 2006).

Conversely, the cell signalling mechanisms in response to endurance training are associated with metabolic adaptations. Adenosine monophosphate-activated protein kinase (AMPK) is one of the main enzymes that monitor the intracellular energy level in order to sustain energy homeostasis (Hardie & Sakamoto, 2006). This is made possible by inhibiting the utilization of adenosine tri-phosphate (ATP) and activating the catabolism of carbohydrate and fatty acid in order to restore ATP levels (Hardie & Sakamoto, 2006). Studies have shown that the activation of AMPK inhibits acetyl co-enzyme A carboxylase and malonyl co-enzyme A, which in turn promotes fatty acid oxidation in the skeletal muscle during exercise (Rasmussen & Winder, 1997; Yu et al., 2003). Another metabolic pathway that initiates mitochondrial biogenesis is the activation of nuclear respiratory factor 1 and nuclear respiratory factor 2 which transcripts the genes that encode mitochondrial respiratory chain proteins (Kelly & Scarpulla, 2004). Finally, the peroxisome proliferator-activated receptor gamma coactivator (PGC-1α) activates and regulates the expression of mitochondrial proteins encoded in the nuclear and mitochondrial genomes (Lin, Handschin, & Spiegelman, 2005). Studies have shown that PGC-1α gene and protein can significantly increase in skeletal muscle following exercise (Adhihetty, Irrcher, Joseph, Ljubicic, & Good, 2003; Baar et al., 2002; Mathai, Bonen, Benton, Robinson, & Graham, 2008). The accumulation of these biogenetic changes that occur from repetitive endurance training stimuli contribute to enhancing aerobic capacity (Hardie et al., 2006).

As discussed above, the cell signalling pathways in which to induce strength and endurance adaptations are vastly different. When the effects of gene expression in response to both strength and endurance exercises were examined, Bolster and colleagues (2002) showed antagonistic effects. The authors investigated whether the translational changes in response to the activation of AMPK affected skeletal muscle protein synthesis. Following the activation of AMPK via injections of 5-aminoimidazole-4-carboxamide 1-β-D-ribonucleoside, results showed a 45% reduction in protein synthesis compared to the control value. Additionally, the protein kinases in mTOR transduction pathway and eIF4E significantly decreased, which demonstrates the molecular mechanisms of the inhibitory effect on protein synthesis. Similarly, Rose and colleagues (2005) examined the phosphorylation of eukaryotic elongation factor, known to inhibit protein synthesis, following cycling exercise at 67% peak oxygen consumption. The results showed a rapid 5-7 fold increase in eukaryotic elongation factor phosphorylation in response to exercise. Given these results, concurrent training would not maximize signalling pathways in order to optimize hypertrophic adaptations since endurance exercises can disrupt the anabolic effect following strength training at a sub-cellular level. Subsequently, training strength in conjunction with endurance exercises would appear incompatible from a molecular standpoint.

2.3.2. Impaired Hypertrophic Adaptation in Response to Concurrent Training

The recurring interference phenomenon in response to concurrent training may predominantly be due to endurance exercises causing inadequate increases in myofibrillar cross sectional area (CSA) essential for muscular strength development (Leveritt, et al., 1999). The orchestration of cell signalling in response to endurance training can regulate gene expression in specific metabolic pathways that inhibits protein synthesis, and as a result, attenuates the ability of the muscle to increase in CSA (Bolster, et al., 2002; Rose, et al., 2005). Studies on rats have shown that endurance exercises can impair hypertrophic adaptations (Klitgaard et al., 1989) and even cause muscular atrophy (Kovanen & Suominen, 1987). If endurance training limits optimal hypertrophic adaptation, this can reduce the morphological capability of the muscle to increase in strength since a strong relationship exists between muscle fibre CSA and muscular force generating capacity (Jones, Bishop, Woods, & Green, 2008). Sipilä and Suominenn (1995) examined the effects of strength and endurance training on lean tissue CSA and thigh and leg CSA in elderly women. The participants were either allocated to a control group or groups that performed strength or endurance exercises. The results showed that the quadriceps and lower leg CSA significantly increased in response to strength and endurance training whereas no significant differences were found for the control groups. However, quadriceps CSA in response to strength training was significantly greater compared to endurance training, which demonstrates that strength training is more effective in inducing hypertrophic adaptations than endurance training for untrained participants.

Similar to the study by Sipilä and colleagues (1995), concurrent training studies have shown greater hypertrophic adaptations for the ST group compared to the CON group (Davis, et al., 2008a; Gergley, 2009; Sillanpää, et al., 2008). For example, Gergley (2009) examined the effects of combining strength training with two different modes of endurance training on lower body strength development. In this study, untrained participants were randomly allocated into an ST group and groups that performed strength and cycling endurance (S-Cyc) and strength and running endurance (S-Run). The three groups trained $2.wk^{-1}$ for 9 weeks and body mass, body composition and 1RM strength measurements were obtained pre– and post-training. The results showed that when men and women were combined, the increase in body mass for the ST group was significantly greater than S-Cyc– and S-Run groups. When men only were Fanalysed, body mass for the ST group was significantly greater than S-Cyc– and S-Run groups and body fat percentage for the ST group was significantly smaller than S-Cyc- and S-Run groups. Bilateral leg press 1RM was significantly greater for men and women for the ST group compared to S-Cyc– and S-Run groups. The ST group showed greater increase in body mass and reduction in BF% compared to the S-Cyc– and S-Run groups. These findings suggest that strength training alone can induce hypertrophic adaptations to a greater degree than concurrent training, regardless of the mode of endurance training. Additionally, the greater increase in muscular strength found for the ST group compared to the S-Cyc– and S-Run groups demonstrates the importance of increasing fat free mass (FFM) for strength gains.

Davis et al (2008a) produced two types of concurrent training protocols and analysed the effects of these protocols on muscular strength, endurance and body composition in female college athletes. These training protocols consisted of participants from one group undertaking serial concurrent exercise and the other group of participants undertaking integrated concurrent exercise. The serial concurrent exercise group performed strength exercises and endurance exercises continuously at 60-85% heart rate reserve and the integrated concurrent exercise group performed the same strength exercises, however, performed cardioacceleration by vigorously running for 30-60 seconds in-between each set of strength training exercises. Following training, it was found that both serial and integrated concurrent exercise groups significantly increased strength, endurance and FFM. However, the integrated concurrent exercise group produced discernibly greater strength and FFM compared to the serial concurrent exercise group. The same authors previously showed that cardioacceleration pre-empted delayed on-set of muscle soreness (DOMS) and possibly due to increased blood flow efficiently removing inorganic phosphates and hydrogen accumulation which have been shown to disturb muscular contractility (Davis, Wood, Andrews, Elkind, & Davis, 2008b). Subsequently, the increase in strength and FFM found in both serial and integrated concurrent exercise groups demonstrates the association between strength development and hypertrophic adaptations. Also, because differences in AMPK activation exists between intermittent and continuous endurance exercise (Koshinaka et al., 2008), alteration in the intensity of endurance exercises may have altered the degree of interference in strength adaptations as the strength development for serial was less compared to the integrated concurrent exercise group.

In addition to the inhibitory effects for increases in FFM found in response to combined strength and endurance training, studies have also shown that the increase in the CSA of type 1 fibres are impaired with concurrent training whereas the increase in CSA of type 2 fibres appears to be similar with strength training (Bell, et al., 2000; Kraemer et al., 1995; McCarthy, et al., 2002; Putnam, et al., 2004). A study conducted by Kraemer et al (1995) examined the compatibility of high intensity strength and endurance training on skeletal muscle adaptations and subsequent strength and power development. Whilst no differences were found in strength development between the ST group and the CON group, the results showed that power output increased for the ST group only. For fibre-type CSA, the findings showed significant increases in muscle fibre area of type 1, 2a and 2c for the ST group; however, there was only an increase in type 2a for the CON group and a decrease in type 1 and 2c fibre types for the END group. These findings suggest that fibre-type adaptation differs according to the mode of training which may contribute to attenuation of performance improvements with concurrent training compared to single-mode training methods.

Similar to the study conducted by Kraemer et al (1995), McCarthy et al (2002) found significant increases in the CSA of type 1 fibres in response to strength training only, and Putnam et al (2004) found a 2.9-fold greater increase in the CSA of type 1 fibres in response to strength training only compared to combined strength and endurance training. Bell et al (2000) compared hypertrophic adaptations between strength training and concurrent training by examining the CSA of type 1 and 2 fibres. The results showed increases in CSA of both type 1 and 2 fibres 6 and 12 weeks following strength training, however, the increase in fibre CSA for type 2 fibres were only found 12 weeks following concurrent training. The earlier onset of an increase in muscle fibre CSA, especially for type 1 fibres, demonstrates greater sensitivity of muscle fibre hypertrophy in response to strength compared to concurrent training. These studies show that fibre type hypertrophic adaptations are induced according to the mode of training, and that increases in type 1 fibres are predominantly attenuated in response to concurrent training. Additionally, of the four studies mentioned above, three of the studies (Bell, et al., 2000; Kraemer, et al., 1995; Putnam, et al., 2004) showed greater increase in either strength or power output for the ST group compared to the CON group. Subsequently, whilst type 2 fibres have greater force generation capacity per CSA compared to type 1 fibres, the inhibition in muscle fibre type 1 hypertrophy in response to concurrent training appears to attenuate strength development. There has been speculation that the selective hypertrophic adaptations to muscle fibre type may be due to cellular adaptation causing antagonism of combined strength and endurance training stimuli (Kraemer, et al., 1995). Bell et al (2000) also suggested that the addition of endurance training may have optimised oxygen kinetics due to the imposed oxidative stress on the muscles, and subsequently reduced hypertrophy of type 1 fibres in response to concurrent training. In light of the above, interference in hypertrophic adaptations during and following concurrent training may contribute to attenuation in strength development.

2.3.3. Fibre-type Distribution in Response to Concurrent Training

The increase in muscle fibre CSA following training depends on the mode of exercise undertaken and the muscle fibre-type recruited. Strength training increases the CSA of both type 1 and type 2a fibres although type 2a CSA appears to increase the greatest (Kraemer, et al., 1995). In contrast, concurrent training has been shown to only increase type 2a fibres and endurance training has been found to reduce the CSA of type 1 and 2c fibres (Kraemer, et al., 1995). In similar fashion to the differences in hypertrophic adaptations between muscle fibre type, studies have shown fibre-type transitions and the subsequent effect on strength development to occur in response to training. These transitions in muscle fibre type are dependent on the mode, intensity and the duration of the training stimulus which alters the functional direction from fast to slow and in the metabolic direction from glycolytic to oxidative myosin heavy chain (MHC) isoforms (Trappe et al., 2000). Based on the MHC isoforms, four pure fibre types, which are expressed as a single MHC isoform, have been identified: fast type 2b, 2d/x, 2a and slow type 1 (Pette, 2002). Additionally, hybrid MHC isoforms are categorized by the combinations of pure MHC isoforms (Schiaffino & Reggiani, 1996).

When examined as a continuum from fast to slow fibres, hybrid MHC fibres are expressed as an intermediate between the pure MHC isoforms (**Figure 2.1.**) (Pette, 2002). For example, MHC1 + MHC2a = type 1/2a; MHC 2a + MHC 2d/x = type 2a/d; MHC 2d/x + MHC2b =

type 2d/b. These fibre-type transitions occur from fast to slow in response to exercise, however, the transition is lead in the opposite direction with immobilization and detraining (**Figure 2.1.**) (Andersen et al., 2005). Specifically, strength training exercises appear to produce subtle fibre type alterations with a significant increase in the percentage of type 2ab and a concomitant reduction in type 2b fibres (Campos et al., 2002; Hather, Tesch, Buchanen, & Dudley, 1991). These fibre type changes have also been associated with an increase in maximal strength, which shows that the conversion from fibre type 2b to fibre type 2ab may contribute to enhanced strength development. In response to endurance training, a shift from muscle fibre glycolytic to oxidative conversions has been shown (Gjøvaag & Dahl, 2008). Thayer and colleagues (2000) showed that 70.9% of muscle fibres amongst endurance athletes with more than a decade of training were type 1 fibres compared to the sedentary group with only 37.7% of type 1 fibres. Also, the percentage of type 2a fibres in the endurance athletes was significantly less compared to the sedentary group.

Muscle fibre type

Type 1 – Type 1/2a – Type 2a – Type 2a/d – Type 2d/x – Type 2d/b – Type 2b

MHC isoform alterations

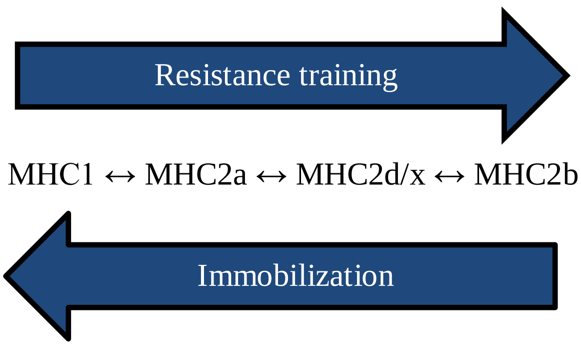

Figure 2.1. Continuum of slow to fast muscle fibre type and myosin heavy chain (MHC) isoform alterations in response to training.

Although numerous studies on fibre type distribution in response to strength or endurance training exist, there is a paucity of literature examining this morphological adaptation in response to concurrent training. The few studies that have examined fibre type changes in response to concurrent training have reported minimal differences in fibre type transitions (Kraemer, et al., 1995; Nelson, Arnall, Loy, Silvester, & Conlee, 1990; Sale, et al., 1990) and this has been associated with limited interference in strength development (Nelson, et al., 1990; Sale, et al., 1990). The study conducted by Kraemer and colleagues (1995), showed inhibition occurring in both strength and power in response to concurrent training even though little difference in fibre type alteration was found. The attenuation in strength development found by Kraemer et al (1995) does not follow previous studies that have shown an association between fibre type alteration and adaptations induced following strength and endurance training (Bell, et al., 2000; Putnam, et al., 2004). Although the interference in strength adaptations may be related to factors other than fibre type (i.e. hormonal changes and hypertrophic adaptations), subtle changes in MHC components may not have been found since histochemical techniques that only displays changes in pure MHC isoforms had been used by Kraemer et al (1995).

For example, Kraemer et al (1995) showed a non-significant increase (73%) in type 2a fibre percentage following strength compared to concurrent training (39%). Additionally, a transition from type 2b to 2a fibres appeared to occur in both the ST group and the CON group. Subsequently, assumptions can be made that MHC 2d/x to MHC 2a isoform transitions could have been observed, provided that immunohistochemical techniques were incorporated. Recent studies using immunohistochemichal methods and protein electrophoresis have shown a reduction in MHC 2d/x, a concomitant increase in MHC 2a and either an increase or no changes occurring in slow MHC isoform content (Liu, Schlumberger, Wirth, Schmidtbleicher, & Steinacker, 2003; Parente et al., 2008; Williamson, Gallagher, Carroll, Raue, & Trappe, 2001). The results obtained from these studies have also shown enhanced strength development, which suggests that MHC isoform transition towards MHC 2a from either MHC 1 or MHC 2d/x induces muscular strength adaptations.

A study conducted by Putnam et al (2004) utilized this immunohistochemical method in order to analyse the MHC content and fibre type changes in response to concurrent training. The results showed that MHC 2a significantly increased only for the CON group and MHC 2d/x decreased similarly between ST and END groups whereas a 2-fold decrease in MHC 2d/x was observed for the CON group. Changes in fibre types occurred mainly for the ST group, where the proportion of type 1/2a hybrid fibres significantly increased, whereas no differences in this fibre population were detected for the CON group. Knee extensor strength increased for all groups, however, in the order of ST–, CON– and END groups. The lower strength gains found with the CON group compared to the ST group can be associated with greater transitions from fast-to-slow MHC isoforms. Such MHC isoform conversions have been shown to reduce force development and subsequent lower power output (Stienen, Kiers, Bottinelli, & Reggiani, 1996; Widrick, Stelzer, Shoepe, & Garner, 2002).

In light of the above studies, the results show that strength is impaired when fibre type conversions occur from a fast-to-slow direction; however, strength is increased if such conversions occur within fast fibre subtypes (Hostler et al., 2001; Kadi & Thornell, 1999). In contrast, endurance training appears to induce muscle atrophy and increase the proportion of type 1 fibres (Fitzsimons, Diffee, Herrick, & Baldwin, 1990). With this in mind, concurrent training may cause antagonistic responses through protein expression and fibre subtype transitions, consequently impairing strength development.

2.4 Interference of Endurance Development with Concurrent Training

Whilst the majority of the studies have shown attenuation in strength development following concurrent training, a number of studies have also shown a compromise in the development of VO_{2max} (Dolezal & Potteiger, 1998; Glowacki, et al., 2004; Gravelle & Blessing, 2000; Nelson, et al., 1990) and 4 km running time-trial performance (Chtara, et al., 2005). For example, Nelson et al (1990) examined the effects of combining strength and endurance training regimens for 20 weeks on muscular strength and cardiovascular endurance adaptations. Endurance and strength indices were determined using cycling VO_{2max} tests and lower extremity isokinetic measures for increased torque production, respectively. Whilst the increase in VO_{2max} was similar between the END group and the CON group at the 11th week of concurrent training, the END group underwent a significant increase in VO_{2max} with no differences for the CON group at the completion of training. Recent studies conducted by Dolezal et al (1998) and Glowacki et al (2004) also showed sub-optimal VO_{2max} measures following concurrent training, although the onset of interference in endurance adaptation found by Dolezal et al (1998) and Glowacki et al (2004) was earlier compared to findings by Nelson et al (1990).

2.5. Acute Mechanisms for the Interference of Endurance Development

The attenuation in strength development as a result of concurrent training has been associated with a compromise of hypertrophic adaptations, alterations in neural recruitment patterns, alterations in muscle fibre type distributions and physiological disturbances at the molecular level (Baar, 2006; Leveritt et al., 1999). However, the mechanisms contributing to sub-optimal endurance adaptations have received little attention. This may be because the interference of strength development has been shown to be more pronounced than the interference of endurance development during and following concurrent training (Dudley & Djamil, 1985; Hennessey & Watson, 1994; Murphy & Wilson, 1996; Nelson, et al., 1990). Nonetheless, Nelson et al (1990) reported sub-optimal endurance adaptations following concurrent training and suggested that the compromise in endurance development may be due to strength-training-induced reductions in mitochondrial volume associated with hypertrophic adaptations. An earlier study by MacDougall et al (1979) also reported an inverse relationship between mitochondrial volume density and the number of type 2a muscle fibres. Furthermore, Nelson and colleagues (1990) showed an increase in citrate synthase and myokinase for the END group although no differences in these oxidative enzymes were found for the CON group.

The reduction in mitochondrial density and oxidative enzymatic activities induced by strength training may be responsible for sub-optimal endurance adaptations during concurrent training. However, a recent study reported that a session consisting of strength and endurance training increased expression of PGC-1 alpha to a greater extent than pure endurance training

(Wang, Mascher, Psilander, Blomstrand, & Sahlin, 2011), which is a key controller of oxidative enzyme expression. Furthermore, reports have shown that strength training improved RE and distance running performance (Ferrauti, Bergermann, & Fernandez-Fernandez, 2010; Paavolainen, Häkkinen, Hamalainen, Nummela, & Rusko, 1999; Saunders, Pyne, Telford, & Hawley, 2004a; Spurrs, Murphy, & Watsford, 2003) possibly due to strength gains and enhanced neural recruitment patterns (Cormie, McGuigan, & Newton, 2010; del Olmo, Reimunde, Viana, Acero, & Cudeiro, 2006; Kraemer, 1988). Subsequently, whilst evidence suggests interference of strength development in response to concurrent training as a result of disturbances at cellular and molecular levels, such complex physiological processes remains unclear for sub-optimal endurance adaptations.

One possible mechanism contributing to the interference in endurance development due to concurrent training is the acute carry-over effects of fatigue between strength and endurance training sessions. Indeed, it has been suggested that residual fatigue generated by the endurance component of concurrent training may compromise the ability of a muscle to produce optimum force during strength training sessions, known as the "acute hypothesis" (Craig, et al., 1991). The contractility of a muscle is important during strength training as it determines the magnitude of strength stimulus required for strength development (Atha, 1981). If sufficient contractility is not generated by the muscle during each training session, optimal strength adaptations will not occur. Therefore, the "acute hypothesis" contends that simply prescribing strength and endurance exercises in a training program does not account for the interference phenomenon, but rather, the duration between the two modes of exercises may determine whether concurrent training causes attenuation in strength development.

Indeed, reports have shown that 40-60 minutes of cycling reduces muscle force generation capacity for up to 6 hours (Bentley, et al., 2000; Bentley, et al., 1998) and up to 48 hours following a marathon (Millet et al., 2002). Accordingly, endurance training may impair the quality of subsequent strength training sessions because the muscle's ability to produce force is essential to induce training stimulus for strength adaptation. However, this mechanism may also apply if these modes of exercises are performed in the reverse order because endurance exercises are executed with repetitive sub-maximal contractions. Subsequently, strength training may impair the quality of an endurance training session as a result of residual fatigue.

The abovementioned point was investigated by Chtara et al (2005) who examined the sequence of strength and endurance training on endurance adaptation (i.e. 4 km time trial performance). The authors reported that endurance development was compromised when strength training preceded endurance training sessions in comparison to the reverse order. These results indicate that residual fatigue generated by the preceding strength training sessions may have compromised the quality of subsequent endurance training sessions and therefore hampered training stimulus for optimum adaptations. Unfortunately, the acute detrimental effects of strength training on the quality of endurance training sessions were not examined by Chtara and colleagues (2005). Nonetheless, reports have shown that strength training impaired RE (Palmer & Sleivert, 2001) and sub-maximal cycling performance (Deakin, 2004) 8– and 3– hours post, respectively. Furthermore, strength training has been shown to impair repeated sprint ability (Twist & Eston, 2005) and time-trial running performance (Marcora & Bosio, 2007) 24 hours post. Subsequently, strength training may cause acute detrimental effects on endurance performance that may compromise the quality of endurance training sessions.

2.6. Mechanisms for the Acute Detrimental Effects of Strength Training on Endurance Performance

The compromise of endurance performance following strenuous exercises has been attributed to a reduction in muscle force generation capacity as a result of central and peripheral fatigue (Humphry et al., 2004; Kawakami, Amemiya, Kanehisa, Ikegawa, & Fukunaga, 2000; Lentz & Nielsen, 2002; Loscher & Nordlund, 2002), glycogen depletion (MacDougall, Ray, & McCarteny, 1988; Pascoe, Costill, Fink, Robergs, & Zachwieja, 1993; Robergs et al., 1991), muscle damage and soreness (Chen, Nosaka, Lin, Chen, & Wu, 2009; Chen, Nosaka, & Tu, 2007; Molina & Denadai, 2012) and alterations in the kinematics of endurance performance (Kellis & Liassou, 2009; Mizrahi, Verbitsky, & Isakov, 2000). Given the evidence of potential harm that strength training may have on the quality of subsequent endurance training sessions, consideration of the acute responses of strength training may shed light as to the mechanisms responsible for the attenuation of endurance performance and subsequent adaptation.

2.6.1. Neuromuscular Fatigue

2.6.1.1. Neuromuscular Fatigue in Response to Strength Training

The reduction in maximal force production due to exercise-induced fatigue can be caused by an impairment of the motor system performance (Gandevia, 2001). With repetitive maximal and submaximal contractions, the neural drive declines and the motor neurons become less responsive to synaptic stimulation (Taylor, Todd, & Gandevia, 2006). This decrement of neural function in response to exercise can originate from peripheral and/or central sites of the nervous system. Peripheral fatigue occurs at or distal to the neuromuscular junction and is represented by a decline in twitch force and the loss of force-generating capacity of the muscle itself (St Clair Gibson & Noakes, 2004). Alternatively, central fatigue occurs when voluntary contraction of a muscle reaches failure and is observed if nerve stimulation evokes an increase in force production during maximal voluntary effort (Bigland-Ritchie, Jones, Hosking, & Edwards, 1978; Taylor, et al., 2006).

The use of electromyography (EMG) is a common method to determine the relationship between the degree of neuromusuclar fatigue and reduction in maximal voluntary contraction (MVC) (Enoka, 2002). Studies have reported a significant reduction in both integrated EMG and torque production after a bout of repetitive knee extensions (Häkkinen, Kraemer, & Newton, 1997; Hisaeda, Shinohara, Kouzaki, & Fukunaga, 2001; Pincivero, Coelho, & Campy, 2008). A reduction in these two variables suggests that neural fatigue resulted in a decrease in strength performance. The twitch interpolation method is another technique that is commonly employed to determine presence of central fatigue. An increase in force evoked by motor nerve stimulation during MVC indicates the inability of the central processes proximal to the site of motor axon stimulation to contribute to optimum force production (Taylor, et al., 2006). Central fatigue can also emerge due to failure of the supraspinal mechanisms which disturbs motor corotical output as measured by transcranial magnetic stimuluation (Gandevia, 2001).

Numerous studies have investigated muscle force generation capacity following resistive-type exercises in order to identify various neuromuscular mechanisms, such as: the type of neuromusuclar fatigue using the ratio of EMG normalized to the M-wave response, comparison of forces between voluntary and electrically evoked contractions and corticospinal evoked stimulation (Dimitrova & Dimitrov, 2003; Jubeau, Muthalib, Millet, Maffiuletti, & Nosaka, 2012; Klass, Levenez, Enoka, & Duchateau, 2008; Mileva, Sumners, & Bowtell, 2012). For example, research has shown that a reduction of MVC following single-joint exercises can be attributed to periperhal fatigue (Cheng & Rice, 2005; Kawakami, et al., 2000; Klass, Guissard, & Duchateau, 2004; Lentz & Nielsen, 2002; Martin, Millet, Lattier, & Perrod, 2005; Pasquet, Carpentier, Duchateau, & Hainaut, 2000; Rattey, Martin, Kay, Cannon, & Marino, 2006), central fatigue (Humphry, et al., 2004; Loscher & Nordlund, 2002; Sacco, Thickbroom, Byrnes, & Mastaglia, 2000) and a combination of the two types of fatigue (Babault, Desbrosses, Fabre, Michaut, & Pousson, 2006).

Whilst the abovementioned studies report the type and mechanisms of fatigue, the muscle force generation capacity (MFGC) was measured immediately following resistive-type single joint (e.g. elbow- and knee- flexion/extension) exercises. These findings would not be applicable from a concurrent training standpoint given that resistive-type single joint exercises would not impose sufficient stress to impair MFGC for several –hours to –days which is typically observed following traditional strength training sessions consisting of multiple exercises (Brentano & Martins Kruel, 2011; Häkkinen, Pakarinen, Alen, Kauhanen, & Komi, 1988; Rawson, Conti, & Miles, 2007; Vaile, Gill, & Blazevich, 2007). In addition, it is expected that endurance exercises would not be performed at optimum levels immediately following a strenuous training session (e.g. strength training exercises) (McLester et al., 2003; Sayers & Clarkson, 2001), especially when concurrent training is undertaken to maximise adaptation.

Unfortunately, there have been limited investigations to determine the type of neuromuscular fatigue contributing to a reduction in MFGC several –hours to –days following traditional strength training sessions. A study conducted by Michaut et al (2000) examined the effects of 5 sets of 10 maximal eccentric contractions of the biceps brachii. Twitch activation and maximal contraction were significantly reduced from two minutes to 48 hours post exercise indicating that the reduction in muscle force generation capacity may have been the result of peripheral fatigue. Häkkinen et al (1988) examined daily neuromuscular responses to high intensity traditional strength training exercises consisting of full body movements. The strength training sessions were conducted $2.day^{-1}$ over one week and MVC and EMG of the lower extremity were analysed following the first strength training session of each day. The results showed that MVC was consistently reduced over the training week although no differences were found for EMG. Given that the neural properties were unaffected by the strength training exercises, peripheral fatigue may have caused the reduction in MVC.

A study conducted by Medbø and colleagues (2001) found that the elevation in the concentration of the sodium/potassium exchange pump led to a significant increase in full squat 1RM following three months of strength training, which suggests a compelling relationship (r = 0.5) between the peripheral properties of the neuromuscular system and work capacity and further supports that peripheral fatigue may be attributed to neuromuscular propagation failure. Accordingly, whilst various reports have shown that a reduction in

MFGC was due to central fatigue immediately following single joint resistive-type exercises (Humphry, et al., 2004; Loscher & Nordlund, 2002; Sacco, Thickbroom, Byrnes, & Mastaglia, 2000), it appears that peripheral fatigue may predominantly contribute to decrement in muscle performance several –hours to –days following high volume strength training exercises.

2.6.1.2. Impact of Neuromuscular Fatigue on Endurance Performance

The neuromuscular response following long distance running and cycling events has been studied extensively with results demonstrating reductions in MVC due to central and/or peripheral fatigue (Amann, 2011; Millet & Lepers, 2004; Noakes, 2007; Petersen, Hansen, Aagaard, & Madsen, 2007). Romer et al (2007) reported that cycling time to exhaustion was less in hypoxia in comparison to normoxia with a concommitant reduction in potentiated twitch force. These findings indicate that cessation of endurance exercise appears to occur as a result of peripheral fatigue. However, it has also been suggested that termination of exercise occurs due to central fatigue as a protective mechanism from potentially harmful metabolic disturbances to preserve muscular function (Noakes, 1998). In light of this hypothesis, Ansley et al (2004) showed that power output and integrated EMG increased comparatively at the end of a 4 km cycling time trial exercise, indicating that fatigue was centrally controlled. Furthermore, Decorte et al (2010) reported that cycling exercise to failure was associated with central rather than peripheral fatigue. Subsequently, how the mechanisms of neuromuscular fatigue contribute to premature cessation of endurance exercises remains unclear. However, given that strength training has been shown to reduce MVC for 24-48 hours post (Häkkinen, et al., 1988; Michaut, et al., 2000), neuromuscular fatigue generated by a strength training session may compromise the quality of a proceeding endurance training session.

A few studies have examined the impact of strength training on MVC and subsequent endurance performance. Palmer et al (2001) examined the effects of a whole body strength training session on MVC and RE. The results showed that RE was significantly impaired for up to 8 hours post exercise, although torque production was only significantly less immediately following the strength training session. In contrast, Marcora and Bosio (2007) examined repeated vertical jump exercises on MVC, RE and running time-trial performance 24 hours post exercise and showed that running time-trial performance was significantly reduced with a concommitant reduction in torque, with no differences found for RE. Whilst maximal running performance may be related to neuromuscular impairment as shown by Marcora and Bosio (2007), the neuromuscular properties may not be related to sub-maximal endurance performance (i.e. RE). Millet (2011) recently reported that the characteristics of maximal contraction may have an indirect link with running performance as it has been suggested that MVC is progressively reduced in order to sustain RPE during sub-maximal running (Martin et al., 2010). Unfortunately, the few studies that have examined the acute effects of strength training on MVC and endurance performance (Marcora & Bosio, 2007; Palmer & Sleivert, 2001) have not analysed the direct relationship between the two variables. Further investigation is warranted by systematically examining the effect of strength training on MVC and subsequent running performance.

2.6.2. Muscle Glycogen

2.6.2.1. Muscle Glycogen Content following Strength Training

An array of studies have shown that a single bout of endurance exercise induces muscle glycogen depletion (Chasiotis, 1983; Cheetham, Boobis, Brooks, & Williams, 1986; Essen & Kaijser, 1978; Gollnick, Piehl, & Saltin, 1974; Hermansen & Vaage, 1977; Hultman, 1986; Jacobs, Tesch, Bar-Or, Karlsson, & Dotan, 1983). In comparison, there has been limited research examining glycogenolytic effects following strength training. A study conducted by MacDougall et al (1988) showed that muscle glycogen depleted by 25% in the biceps brachii following three sets of 10 repeptitions of elbow flexion/extension exercises. A more recent study by MacDougall and colleagues (1999) reported similar findings where muscle glycogen content of the biceps brachii was reduced by approximately 20% following elbow flexion/extension exercises at 80% of 1RM to failure. In addition, Tesch et al (1986) reported that muscle glycogen content of the vastus lateralis decreased by 26% following repeated sets of resistive exercises of the lower extremity.

A study conducted by Robergs et al (1991) examined high and low intensity (i.e. 70– and 35% of 1RM, respectively) strength training on muscle glycogen content by performing 6 sets of leg extension exercises whilst equating work betweeen the two intensities. The results showed that muscle glycogen content reduced by 38– and 39% following low and high intensity strength training protocols, respectively. These results show that muscle glycogen content is substantially reduced following strength training regardless of training intensity provided that work is equated between high and low training intensities. Pascoe et al (1993) investigated the effect of post-exercise carbohydrate ingestion on the rate of muscle glycogen resynthesis following leg extension exercises at 70% of 1RM to failure. The results showed that muscle glycogen content was reduced by approximately 33% following strength training and returned to 91% of baseline values 6 hours post with post-exercises carbohydrate ingestion. However, muscle glycogen content remained significantly depleted (by approximately 25%) 6 hours following strength training with the absense of post-exercise carbohydrate ingestion. These findings suggest that muscle glycogen depletion can be sustained for several hours following strength training. Subsequently, the glycogenolytic effect elicited by strength training could impact on endurance performance decrements within the hours following strength training and attenuate optimal endurance training adaptations in concurrent training.

2.6.2.2. Impact of Muscle Glycogen Depletion on Endurance Performance

The compromised muscular contractility following strenous exercises could be caused by various processes involved in motor unit activation or the translation of the neural signal into muscular force production. Literature suggests that the pathways that impair the neuromuscular properties are strongly dependent on the level of endogenous glycogen (Green, 1990) and that inadequent energy supply may lead to failure of transformation from the neuromuscular event to mechanical force production (Luckin, Biedermann, Jubrias, Williams, & Klug, 1991). Muscle glycogen was the dominant fuel source at workloads above 65-70% of VO_{2max} (Romijn et al., 1993; van Loon, Greenhaff, Constantin-Teodosiu, Saris, & Wagenmakers, 2001) during endurance exercise. The association between muscle glycogen content and endurance performance has been most apparent during cycling and running exercises performed at intensities from 65 to 85% of VO_{2max} (Laurent et al., 2000; Williams, Raven, Fogt, & Ivy, 2003; Wilson, Gusba, Robinson, & Graham, 2007). Impaired performance in prolonged and high intensity endurance exercise has been attributed to energy substrate depletion, which include muscle and liver glycogen (Bosch, Weltan, Dennis, & Noakes, 1996; Lima-Silva, De-Oliveira, Nakamura, & Gevaerd, 2009), blood glucose (McConell, Snow, Proietto, & Hargreaves, 1999) and phosphocreatine (PCr) (Coyle & Montain, 1992; Dupont, Blondel, & Berthoin, 2003).

The loss of glycogen content has been postulated to cause a reduction in ATP concentration due to the inability to sustain glycolytic flux rate and ATP regeneration (Keller, Kolbe, Herken, & Lange, 1976; Parkhouse, Dobson, & Hochachka, 1988). Following the ATP-PCr system, glycolysis is the metabolic pathway essential during high intensity exercise in order to regenerate ATP via oxidative phosphorylation (Calhoun & Swartz, 2007). It also functions to generate citric acid cycle intermediates, such as pyruvate, which are essential for the formation of acetyl co-enzyme A to be oxidized for energy production (Howlett, Heigenhauser, & Spriet, 1999). Numerous studies have shown a reduction in total adenine nucleotide pool (i.e. ATP + adenosine diphosphate + adenosine monophosphate) and an increase in iosine monophosphate following cycling (Karatzaferi, de Haan, Ferguson, van Mechelen, & Sargeant, 2001; Zhao, Snow, Stathis, Febbraio, & Carey, 2000) and running exercises (Stathis, Febbraio, Carey, & Snow, 1994). However, studies have also shown no significant differences in ATP concentration when compared between pre– and post endurance exercise even though significant depletion in glycogen occurred (Baldwin et al., 2003; Norman, Sollevi, Kaijser, & Jansson, 1987). Further, it has been shown that compromise in muscular performance can still occur without alterations in adenosine monophosphate, iosine monophosphate, adenosine, creatine, pyruvate and lactate (Cooke &

Pate, 1990; Vollestad & Sejersted, 1988). These findings challenge earlier speculations of loss in muscular force production consequent to reduction in ATP hydrolysis (Hultman, Spriet, & Soderlund, 1986).

The reduction in force production with the absent changes in ATP concentration and the by-products of ATP hydrolysis demonstrates that glycogen may have non-metabolic roles in muscular function. Speculations have been given that impairment of the sarcoplasmic reticulum is a major cause of contractile failure due to the inability to sustain calcium concentration and subsequent activation of the contractile properties (Green, 1990). Evidence shows that stimulation of the sarcoplasmic reticulum attenuated the rate of calcium release (Allen, Lee, & Westerblad, 1989), which was indicative of sarcoplasmic reticulum failure and signified reductions in maximal force capacity (O'Brien et al., 1991). Additionally, reductions in calcium uptake and calcium ATPase activity has been associated with glycogen depletion (Byrd, Bode, & Klug, 1989). It is suggested that sacroplasmic reticular function may be dependent on the glycogen status of the muscle fibres, such as alteration in the glycolytic intermediates and free radicals as remnants of energy production (Byrd et al., 1989). It has been reported that sarcoplasmic reticular function fails as a protective mechanism in order to prevent an energy crisis (Ball-Burnett, Green, & Houston, 1991) and to protect the cellular energy state during contractions (Hancock, Brault, & Terjung, 2006).

Thus, the growing body of evidence indicating the dependence on endogenous muscle glycogen content during endurance exercise suggests the possible acute interference that strength training may have on endurance performance. In fact, recent studies have examined the impact of muscle glycogen depletion on endurance performance (Carter, Pringle, Boobis, Jones, & Doust, 2004; Gualano et al., 2011; Suriano, Edge, & Bishop, 2010). For example, Suriano et al (2010) examined the effects of 60 minutes of cycling on muscle glycogen content and subsequent RE. The results showed a significant reduction in muscle glycogen content with a concommitant increase in oxygen consumption (VO_2) during the RE test. In addition, a significant relationship (r = 0.57) was found between changes in VO_2 and the magnitude of total glycogen depletion. Furthermore, the reduction in muscle glycogen content claimed to have impaired RE was approximately 20%, which is less than previous reports that have examined muscle glycogen content immedialy post to 6 hours following resistive-type strength training (i.e. 25-39% loss of muscle glycogen content) (Pascoe, et al., 1993; Robergs, et al., 1991). This relationship beween alterations in muscle glycogen content and VO_2 kinetics reported by Suriano et al (2010) demonstrate that muscle glycogen depletion as a result of strenous exercises (e.g. traditional strength training sessions) may contribute to attenuation in subsequent endurance performance. However, there is still limited evidence of the relationship between alterations in muscle glycogen content and endurance performance following strength training which warrants investigation.

2.6.3. Muscle Morphology

2.6.3.1. Exercise-induced Muscle Damage and Delayed-onset Muscle Soreness following Strength Training

Exercise-induced muscle damage (EIMD) has been suggested to occur by unaccustomed exercise or repetitive eccentric contractions (Howatson et al., 2008) which results in a reduction in MVC (Molina & Denadai, 2012; Plattner, Baumeister, Lamberts, & Lambert, 2011; Skurvydas, Brazaitis, Kamandulis, & Sipaviciene, 2010), increase in muscle soreness (Hunter et al., 2012), increased muscle stiffness and swelling (Nosaka & Clarkson, 1996) and increased intramuscular proteins (Thompson, Maynard, Morales, & Scordilis, 2003). In particular, the high intensity eccentric components of strength training have been suggested to cause EIMD (Brentano & Martins Kruel, 2011). Whilst a number of mechanisms responsible for EIMD have been proposed, the exact causative factors remain inconclusive. The hypotheses for the mechanisms of EIMD have been divided into two models. The initial phase which occurs during an exercise bout induces the injury process. Following the initial phase, the secondary phase is caused by the disturbance of calcium homeostasis, calcium overload and the resultant inflammatory responses (Howatson & van Someren, 2008; Tee, Bosch, & Lambert, 2007).

The initial phase of EIMD may be attributed to metabolic and/or mechanical consequences of exercise. The metabolic response of EIMD has been suggested to be caused by hypoxia during exercise. The hypoxic conditions during exercise causes changes in ion concentrations, increases metabolic by-products and reduces ATP which have been shown to induce symptoms similar to EIMD (Byrnes & Clarkson, 1986; De Vries, 1966). The mechanical model of the initial phase of EIMD suggests that resisted lengthening actions during eccentric contractions decreases the number of muscle fibre cross-bridge sites which predisposes the contractile properties to failure (McCully & Faulkner, 1986). The secondary phase of EIMD suggests that the increase of intracellular Ca^{2+} from the extracellular substances causes further muscle damage (Gissel & Clausen, 2001; Mikkelsen, Fredsted, Gissel, & Clausen, 2004). The influx of Ca^{2+} associated with alterations of the sarcoplasmic reticulum (Gissel & Clausen, 2001; Mikkelsen, et al., 2004) activates proteolytic and lipolytic mechanisms that causes disruption of cell membrane and sarcolemma, cell infiltration, fibre necrosis and production of reactive oxygen species (Beaton, Tarnopolsky, & Phillips, 2002; Proske & Morgan, 2001). These processes are followed by phagocytosis where inflammatory responses occur to remove damaged tissue (Tee, et al., 2007), leading to prostaglandin E_2 and leukotriene synthesis (Armstrong, 1990).

One major consequence of myofibrillar disruption is DOMS lasting several days post exercise. Exercise has been shown to induce DOMS immediately post (Nguyen et al., 2009) and peak over the next 24-48 hours (Braun & Dutto, 2003; Clarkson, Nosaka, & Braun, 1992). The production of prostaglandin E_2 in response to muscle damage stimulates type III and IV pain afferents whereas neutrophils permeate through the vascular wall to the damaged site due to leukotriene synthesis. These neutrophils cause further muscle damage via production of free radicals (Nguyen & Tidball, 2003) and attract an influx of protein-rich fluid into the muscle (i.e. oedema swelling). Consequently, repetitive eccentric contractions cause inflammatory responses (Evans et al., 1986), increase intramuscular osmotic pressure and generate pain by the activation of group IV afferents (Friden, Sfakianos, & Hargens, 1986). Subsequently, EIMD appears to be a substantial contributor to DOMS. However, it has been stated that caution should been taken with the use of DOMS as a direct measure of EIMD since muscular functional attenuation occurs prior to the onset of DOMS (Byrne, Twist, & Eston, 2004) and muscular function has been shown to remain decreased whilst soreness dissipates (Michaut, Pousson, Babault, & Van Hoecke, 2002; Nosaka, Newton, & Sacco, 2002). Nonetheless, the perception of pain following eccentric contraction has been reported to increase rating of perceived exertion (RPE) during sub-maximal running (Marcora & Bosio, 2007), indicating that DOMS is an effective measure for determining the mechanisms of changes in perception of work done (e.g. RPE) during exercise as a result of EIMD.

Creatine kinase (CK) is another parameter commonly employed to determine EIMD as it is an indirect measure of myofibrillar damage. It has been reported that CK can be elevated from as early as 6 hours (Baty et al., 2007; Tokmakidis, Kokkinidis, Smilios, & Douda, 2003) and peak from 24-96 hours post resistive-type exercises (Brancaccio, Maffulli, & Limongelli, 2007; Kasper, Talbot, & Gaines, 2002). However, studies have reported poor correlations with alterations in myofibre proteins (e.g. CK, glutamine-oxaloacetic transaminase, slow myosin heavy-chain fragments, lactate dehydrogenase and myoglobin) and muscle function (Clarkson, Byrnes, McCormick, Turcotte, & White, 1986; Clarkson & Ebbeling, 1988; Newham, Jones, & Clarkson, 1987). Newham et al (1987) examined muscle force characteristics and CK following three bouts of repetitive eccentric contractions separated by 2 weeks. The results showed that MVC remained reduced following each exercise intervention, however, CK was unaffected by the second and third bout of the exercises. This dissociation between myofibre proteins and muscle function may be attributed to variability in training background of participants. In fact, inter-individual variation is strongly evident in CK although the magnitude of the attenuation of muscle function is relatively homogenous following eccentric contractions (Clarkson & Ebbeling, 1988). In light of these findings, Warren et al (1999) suggested the incorporation of muscle contractile parameters (e.g. MVC tests) rather than measurement of myofibre proteins when examining the acute effects of muscle-damaging interventions. Subsequently, MVC tests may be an effective method of determining whether acute effects of strength training on endurance performance are influenced by the morphological condition of the muscle.

2.6.3.2. Impact of Exercise-induced Muscle Damage on Endurance Performance

In addition to the reduction in MVC, EIMD has been shown to impair various athletic performance measures, such as peak contraction velocity of biceps (Miles, Ives, & Vincent, 1997), and drop jump performances (Horita, Komi, Nicol, & Kyrolainen, 1999) 24-48 hours post. Whilst these findings suggest that EIMD compromises dynamic muscular contractions at maximal effort, little is known as to whether EIMD impacts endurance performance. Examining the impact that EIMD has on endurance performance may provide insight on how strength training would affect the quality of subsequent endurance training sessions. Braun et al (2003) examined the effects of downhill running on RE 48 hours post, and demonstrated an increase in VO_2 and muscle soreness. Whilst MVC was not examined in the study by Braun et al (Braun & Dutto, 2003), the attenuation of RE may have been attributed to muscle damage as indicated by DOMS. Similarly, Chen et al (2007; 2009) examined the effects on RE 24 hours to 5 days following downhill running. The results showed that VO_2 was significantly greater in conjunction with an increase in CK and myoglobin and a reduction in MVC over the course of the 5 day period. Given the increase in myofibre proteins and reduction in MVC, the authors postulated that the increased physiological cost of running following dowhill running was associated with EIMD.

In contrast, Paschalis et al (2005) reported significant changes in muscle damage indicators (i.e. CK, DOMS and range-of-motion and MVC) 24–, 48–, 72– and 96 hours following 120 maximal eccentric contractions although RE parameters were not affected. Findings by

Marcora et al (2007) were in line with those by Paschalis et al (2005) where 100 bench steps caused significant changes in muscle damage indicators (i.e. CK, MVC and DOMS) 24 and 48 hours post, although no differences were found for the physiological responses of RE. However, Marcora and colleagues (2007) showed that time-trial performance declined as a result of the exercise intervention. Furthermore, Byrne and Eston (2002) reported a significant reduction in 30-second wingate performance as a result of EIMD. It has been suggested that fast twitch muscle fibres are more susceptible to EIMD than slow twitch muscle fibres (Twist & Eston, 2005). Given that fast twitch muscle fibres are predominantly used above anaerobic threshold (AT), EIMD may have a greater impact on subsequent endurance performance at higher intensities. In addition, it appears that the impact EIMD has on endurance performance may be dependent on the volume of work done during resistive-type exercises (e.g. the number of contractions during 30 minutes of downhill running is greater compared to 100-120 eccentric contractions).

In light of the above, EIMD may affect both sub-maximal and maximal endurance performance which appears to be dependent on the volume of work done. However, very little is known of the effects of EIMD on endurance performance at various intensities following strength training sessions consisting of multiple exercises. Scott et al (2003) examined the effects of traditional lower extremity strength training exercises (e.g. squats and lunges) on RE at 12–, 24–, 36– and 60 hours post. Muscle soreness peaked beween 24-36 hours post, although no differences were found in the physiological parameters of RE. However, RPE was significantly greater during the RE test. The authors suggested that the pariticipants perceived the exercises to be harder whilst experiencing DOMS. It has been postulated that perception of pain is related to mechanisms controlling the cardiovascular function (Randich & Maixner, 1984). Furthermore, Robertson et al (1982) suggested that the primary sensory signal for RPE may be derived from local factors whereas the central factors may mediate the local signals in response to cardiopulmonary demands.

In light of the above, DOMS may contribute to increased perception of effort and affect endurance performance. However, the physiological responses of EIMD may also contribute to attenuation of endurance performance. A number of studies using magnetic resonance imaging have shown an increase in inorganic phosphate to PCr ratio as a result of EIMD following resisted eccentric contractions (Lund, Vestergaard-Poulsen, Kanstrup, & Sejrsen, 1998a, 1998b; McCully & Posner, 1992). This metabolic alteration may be attributed to disruption of the sarcolemma or an increase in metabolic rate (McCully, Vandenborne, DeMeirleir, Posner, & Leigh, 1992). Furthermore, Davies et al (2011) examined muscle metabolism and subsequent time-to-exhaustion knee extensor exercises in response to EIMD using magnetic resonance spectroscopy 24 hours following 100 repetitions of squats at 70% of body mass. The results showed an increase of indirect markers of muscle damage (i.e. CK, DOMS and MVC), inorganic phosphate concentration and inorganic phosphate to PCr ratio with a concommitant reduction in knee extensor time-to-exhaustion. Walsh et al (2001) suggested that metabolic alterations in response to EIMD may result in reduced oxygen diffusion as a result of restricted blood flow, sub-optimal mitochondrial respiration and adenosine diphosphate desensitization of mitochondrial respiration. Furthermore, EIMD has been shown to inhibit insulin sensitivity which may resist the uptake of glucose into damaged muslces (Del Aguila et al., 2000; Tuominen et al., 1996). Studies have also shown compromise in glycogen synthesis following eccentric contractions that caused EIMD (Asp, Kristiansen, & Richter, 1995; Kristiansen, Asp, & Richter, 1996; Kristiansen, Jones, Handberg, Dohm, & Richter, 1997). Consequently, alterations in metabolism, attenuation in insulin sensitivity and subsequent inhibition of glucose synthesis may contribute to attenuation of endurance performance as a result of EIMD following strength training.

2.6.4. Changes in running gait due to fatigue

Strenuous resistive eccentric exercises have been shown to cause muscle glycogen depletion (MacDougall, et al., 1988; MacDougall, et al., 1999; Robergs, et al., 1991) and EIMD (Molina & Denadai, 2012; Plattner, et al., 2011; Skurvydas, Brazaitis, & Kamandulis, 2010). These physiological responses decrease ATP concentration, impair ATP regeneration and increase inorganic phosphates. The limited availability of energy substrates may increase the metabolic demand of performing an exercise compared to a non-fatigued condition and thus impair performance. In addition to the metabolic consequences of exercise-induced fatigue, muscle glycogen depletion and EIMD have been suggested to impair sarcoplasmic reticular function (Byrd, 1992; Frias et al., 2005) which is essential for excitation-contraction coupling (Takekura, Fujinami, Nishizawa, Ogasawara, & Kasuga, 2001). Indeed, studies have shown that eccentric exercise reduces muscle force generation capacity for up to 5 days (Chen, et al., 2009). In addition, exercise-induced fatigue has been reported to alter neural recruitment patterns during the performance of various exercises. Plattner et al (2011) recently showed that mucle activity of the biceps brachii decreased during maximal contractions although increased during sub-maximal contractions in response to EIMD, indicating alterations in neural firing patterns and motor unit activity. Furthermore, eccentric contractions have been demonstrated to impair proprioceptive mechanisms by increasing the perception of force generation in comparison to the actual force recorded (Brockett, Warren, Gregory, Morgan,

& Proske, 1997; Saxton et al., 1995). Given that neuromuscular control is imperative for human locomotion, neuromuscular dysfunction in response to strenuous exercises could alter kinematics of endurance performance, impair movement efficiency and decrease the economy of movement (Williams, Cavanagh, & Ziff, 1987).

There is a growing body of evidence suggesting that resistive-type exercise causes alterations in lower extremity running kinematics that have been associated with EIMD (Chen, et al., 2009; Chen, et al., 2007; Paschalis, et al., 2007), DOMS (Dutto & Braun, 2004; Hamill, Freedson, & Clarkson, 1991) and neuromuscular fatigue (Kellis & Liassou, 2009; Mizrahi, et al., 2000). The majority of these studies have shown significant reductions in lower extremity joint range of motion during running (Chen, et al., 2009; Chen, et al., 2007; Dutto & Braun, 2004; Hamill, et al., 1991; Paschalis, et al., 2007). Unfortunately, the investigation of exercise-induced fatigue on the mechanics of other modes of endurance exercises are scarce (e.g. cycling and rowing). This may be due to the equipment restricting the movement to a particular plane of motion, hence causing the biomechanics to be predictable. For example, the pedals on a cycling ergometer predominantly executes lower extremity movement in the sagittal plane with limited variation in range of motion for each cadence. On the other hand, there is greater possibility for movement variation during running, as there is limited equipment conrolling gait. Subsequently, it is reasonable to assume that running gait may be more susceptible to movement variation as a result of fatigue in comparison to others modes of endurance exercises.

It has been hypothesised that lower extremity range of motion following strenuous exercises is restricted due to perception of muscle pain (Hamill, et al., 1991), altered motor unit activation pattern (Braun & Dutto, 2003) and reduced reflex sensitivity and/or decreased ability to use the stretch-shortening cycle (Chen, et al., 2007). This compromise in lower extremity range of motion has been associated with reductions in stride length and an increase in stride frequency during running (Braun & Dutto, 2003). Such biomechanical modifications would elevate energy expenditure due to an increase in the number of muscular contractions for a given running distance. Furthermore, compromise of the stretch-shortening cycle would limit optimum energy transfer between segments, rendering the locomotion inefficient.

A strong correlation (r = -0.8) has been reported between reduction in stride length and increase in VO_2 during a RE test following downhill running (Braun & Dutto, 2003). In addition, Bonacci et al (2010) recently showed that alterations in running kinematics following cycling was related to changes in RE. Subsequently, alterations in running kinematics as a result of exercise-induced fatigue appears to contribute to a decrement in RE. However, the studies that have examined the impact of strenuous exercises on running kinematics have been limited to endurance exercises (Bonacci, et al., 2010; Braun & Dutto, 2003) or eccentric contractions (Dutto & Braun, 2004; Hamill, et al., 1991). Investigation of the effect that traditional strength training exercises have on running kinematics and the impact on the physiological variables of endurance performance is limited. Given the abovementioned evidence, strength training may cause inefficiency in running due to changes in gait pattern. As a result, greater energy expenditure may be required to run a given distance or the athlete may not be capable or running a given distance of what he/she would cover in a non-fatigued condition. A reduction in the total work done due to pre-exisiting fatigue would hamper the quality of the running session.

2.6.5 Summary

In light of the above points, the quality of endurance training sessions during concurrent training appears to be dependent on the acute responses of previous strength training sessions. However, the amount of interference endurance training sessions experience during concurrent training may be dictated by the nature of the training program. For example, the quality of endurance training sessions could be hampered to a greater extent by prescribing strength and/or endurance training sessions that induce a high level of fatigue or due to inadequate recovery periods between strength and endurance training sessions. Subsequently, it is essential to examine whether adaptation induced by concurrent training is dependent on training type or study design (e.g. intensity, volume, contraction velocity, training sequence and recovery period). In addition, to determine whether this adaptation is influenced by the acute responses of strength and endurance training.

2.7. The Effect of Study Design in Concurrent Training Research

According to the concurrent training studies that have been conducted thus far, the level of training adaptations has been inconsistent. Studies have shown that concurrent training can compromise strength but not endurance adaptations (Bell, et al., 2000; Kraemer, et al., 1995; Putnam, et al., 2004), impair endurance adaptations (Chtara, et al., 2005; B.A. Dolezal & Potteiger, 1998; Glowacki, et al., 2004; Gravelle & Blessing, 2000; Nelson, et al., 1990), attenuate neither strength nor endurance adaptations (McCarthy, et al., 2002; Sillanpää, et al., 2008; Wood et al., 2001) or even induce strength and endurance adaptations (Balabinis, et al., 2003; Mikkola, et al., 2007). These discrepancies in results may be due to differences in the design of the study and the type of variables incorporated, such as:

- the characteristics of the participants from trained (Gravelle & Blessing, 2000; Häkkinen, et al., 2003) to untrained (Bell, et al., 2000; Gergley, 2009);
- the mode of strength training from isoinertial (Dolezal & Potteiger, 1998) to isokinetic (Abernethy & Quigley, 1993);
- the intensity of strength training exercises from high (Baker, 2001) to low (Verney et al., 2008);
- the type of strength tests from isoinertial (Glowacki, et al., 2004), isokinetic (Sale, et al., 1990) to power and explosive type tests (Kraemer, et al., 1995);
- the mode of endurance training from cycling (Izquierdo, et al., 2005; Putnam, et al., 2004), running (Dolezal & Potteiger, 1998; Kraemer et al., 2004) to rowing (Gravelle & Blessing, 2000);

- the type of endurance assessments from VO_{2max} tests (Dolezal & Potteiger, 1998; Nelson, et al., 1990), RE tests (Millet, et al., 2002) to running time-trial performance (Chtara, et al., 2005);
- the format of endurance exercises from intermittent (Baker, 2001; Chtara, et al., 2008) to continuous (Glowacki, et al., 2004; Gravelle & Blessing, 2000);
- the duration of the exercise program from as short as 7-11 weeks (Balabinis, et al., 2003; Davis, et al., 2008a) to as long as 16-22 weeks (Izquierdo, et al., 2005; Sale, et al., 1990; Sillanpää, et al., 2008).

To further complicate matters, concurrent training studies have incorporated different types of experimental groups. A number of studies have included ST–, END– and CON groups and have shown enhanced strength and endurance adaptations for all groups examined (Dolezal & Potteiger, 1998; Ferketich, Kirby, & Alway, 1998; Häkkinen, et al., 2003). However, when ST–, END– and CON groups were compared, several studies have shown attenuation in the development of strength and power (Chtara, et al., 2008; Kraemer, et al., 1995) or endurance (Dolezal & Potteiger, 1998; Hennessey & Watson, 1994). In addition, some studies have shown that concurrent training induced strength and endurance adaptations when compared to a control group that did not undertake training (Dolezal & Potteiger, 1998; Takeshima et al., 2004). However, these studies (Dolezal & Potteiger, 1998; Takeshima et al., 2004) did not include an ST group or an END group. Such a study design is limiting, since the exercise induced-adaptation could not be compared with groups that could have performed either mode of exercise alone. If these studies incorporated ST– and END groups with equivalent training volume and duration as the CON group, the development of strength or endurance from the CON group compared to the ST or END groups alone may have been suboptimal.

In light of the above, the disparity in training outcomes between concurrent training studies could be due to differences in the type of training variables incorporated. To determine whether training methodology impacts on the type and magnitude of training interference as a result of concurrent training, it is essential to analyse the type of training variables that have been used by various concurrent training studies. With this, certain trends in training methodology could be ascertained between concurrent training studies and their contribution to training interference. Subsequently, whilst concurrent training has been shown to induce sub-optimal strength and endurance adaptations, the following sections will predominantly focus on the types of training variables (e.g. intensity/volume, recovery period, mode of exercise, training frequency) used by concurrent training studies and the effect that these training variables appear to have had on endurance adaptation. In so doing, research questions can be generated regarding the acute effects of various strength training methodologies on endurance performance. This would assist in conducting studies to systematically analyse the acute responses of the “interference phenomenon” specifically for endurance adaptation.

2.7.1. Different Modes of Endurance Exercises

Studies have shown interference in strength, power and endurance adaptations following concurrent training consisting of strength and running (Chtara, et al., 2005; Dolezal & Potteiger, 1998; Glowacki, et al., 2004; Kraemer, et al., 1995), strength and rowing (Gravelle & Blessing, 2000) or strength and cycling exercises (Izquierdo, Ibanez, Kraemer, Larrion & Gorostiaga, 2004; Putnam, et al., 2004). However, studies have also shown that concurrent training improved strength and endurance qualities with running (Balabinis, et al., 2003; Chtara, et al., 2005) but had no improvement on strength and endurance development with cycling exercises (Ferketich, et al., 1998; Sale, et al., 1990). When strength training was combined with both cycling and running exercises, results showed no pre– to post training differences in strength (Wood, et al., 2001), no differences in endurance measures (Millet, et al., 2002; Shaw & Shaw, 2009) nor compromise in strength and power (Izquierdo, et al., 2005). One component contributing to the disparity in results between the concurrent training studies may be due to differences in the modes of endurance exercises incorporated.

Studies have shown higher VO_{2max} values when greater muscle mass is engaged to perform a particular exercise (Bergh, Kanstrup, & Ekblom, 1976; Ogata & Yano, 2005). For example, running has been shown to produce higher VO_{2max} measures than cycling (Hermansen & Saltin, 1969; Matsui, Kitamura, & Miyamura, 1978) since work is done from both the upper and lower extremity during running compared to cycling which predominantly involves the lower extremity. Given that running engages a greater number of muscle groups and thus would use greater energy expenditure than cycling at the same intensity (Millet, et al., 2009), running may cause greater physiological stress than cycling and consequently impair strength and/or endurance adaptations during concurrent training. In fact, Dolezal et al (1998) and Glowacki et al (2004) incorporated running as part of endurance training sessions, and to date, were the only studies that have shown sub-optimal development in both strength and endurance adaptations. Furthermore, Gergley (2009) examined the effects of different modes of endurance exercises in a concurrent training program by comparing cycling on a cycle ergometer and walking on an inclined treadmill. The prescribed lower extremity strength training exercises were the same between groups. The results showed a greater percentage in strength gains with cycling than when walking was combined with strength training. As walking requires work from the upper and lower body compared to cycling where movement predominantly occurs at the lower body, a greater level of physiological stress may have been created on the body. Subsequently, running may cause even greater interference on training adaptations than cycling and/or walking due to greater level of stress imposed on the body.

In conjunction with the type of endurance exercises incorporated in the concurrent training studies thus far, the inconsistent findings regarding endurance adaptations may also be due to the type of endurance assessment conducted. The majority of the concurrent training studies have incorporated VO_{2max} tests in order to determine endurance development (Balabinis, et al., 2003; Glowacki, et al., 2004; Gravelle & Blessing, 2000; Häkkinen, et al., 2003; Kraemer, et al., 1995; Leveritt, et al., 2003; Mikkola, et al., 2007; Nelson, et al., 1990; Sale, et al., 1990). Of the concurrent training studies that incorporated VO_{2max} tests, only a few have shown sub-optimal endurance adaptations (Dolezal & Potteiger, 1998; Glowacki, et al., 2004; Gravelle & Blessing, 2000; Nelson, et al., 1990). Basing findings solely on VO_{2max} as an indication of endurance development following concurrent training is problematic given that endurance adaptations can be induced in various forms such as improvement in muscular endurance and running efficiency (Hausswirth, Bigard, & Guezennec, 1997). Consequently, incorporating measures such as running time-trial performance, running time to exhaustion and/or RE may better represent endurance adaptation as a result of concurrent training.

A study conducted by Chtara et al (2005) showed that the combination of strength and endurance training impaired 4 km running time trial performance amongst trained runners. Subsequently, the interference of endurance adaptation may be more apparent with running performance measures than VO_{2max} measures. In contrast, Millet et al (2002) reported no differences in RE between a CON group and END group following a concurrent training program. Based on the findings by Chtara et al (2005), attenuation in RE should have been found in the study by Millet et al (2002) since the energy cost of running during RE is influenced by both aerobic and anaerobic metabolism (Saunders, et al., 2004a). However, Chtara et al (2005) incorporated strength and endurance training sessions on the same day, whereas only two strength training sessions were performed per week during the study by Millet et al (2002). In addition, Chtara et al (2005) periodised the strength training program by incorporating strength-endurance and explosive-type exercises whilst Millet et al (2002) prescribed lower body only exercises which were based purely for strength development. Subsequently, it appears that the interference in endurance development following concurrent training could also depend on the nature of the strength training session prescribed in conjunction with the type of endurance assessment conducted.

Given that the effect of concurrent training on endurance adaptation could be dependent on the methods of strength training, it would be interesting to systematically investigate the acute effects of altering the volume of strength training on endurance performance. Deakin (2004) examined the effects of whole body versus lower body only strength training on cycling efficiency, and showed that whole body strength training increased the physiological cost of cycling more than lower body only strength training. These findings suggest that the impact that strength training has on cycling performance may be dependent on strength training volume. However, given the physiological differences in running and cycling (Millet, et al., 2002), it remains unclear whether differences in the methods of strength training would affect running performance.

2.7.2. Different Intensities of Strength and Endurance Training

The type and extent of training adaptation is predominantly determined by training intensity and volume (Kraemer, et al., 2002). For example, strength development predominantly occurs when strength training is performed at a high intensity and low volume (5-6 sets of 1-6 repetitions), hypertrophic adaptations are induced when performed at a moderate to high intensity and moderate volume (three to four sets of 8-12 repetitions) and muscular endurance increases when performed at low intensity and high volume (three to four sets of 15 repetitions or more). Alternatively, anaerobic endurance performance increases when the intensity of running and cycling training is performed close to VO_{2max} (80-100% of VO_{2max}) whereas aerobic endurance increases when running and cycling training are performed continuously at slightly below AT (70-80% of VO_{2max}) (Wenger & Bell, 1986).

As training adaptation is dependent on the intensity and volume of training (Kraemer, et al., 2002), training variables within a concurrent training program may be set such that the interference of strength and/or endurance development is minimized. Docherty et al (2000) proposed the "zone of interference" effect, suggesting that the degree of interference of strength performance may be dictated by the intensity and volume of strength and endurance training performed on the same muscle groups. The authors hypothesized that strength performance would be most detrimental when strength and endurance training were performed with variables that induce peripheral fatigue. Such training includes strength training performed to induce hypertrophic adaptations (multiple sets of 8 to 12RM) and endurance training performed in order to increase maximal aerobic power (high intensity interval training). This maximal antagonistic effect has been suggested to occur since hypertrophic strength training initiates intramuscular protein synthesis and stresses the anaerobic system as a result of lactic acid accumulation. Such physiological responses would also occur due to high intensity endurance training, which would result in disrupting the functional properties of muscular contraction. Alternatively, given that high intensity strength training predominantly affects the neuromuscular system, such as the inability to recruit motor units, if high intensity strength training was combined with low to moderate endurance training, the interference could be limited.

An investigation of the acute interference effect between different intensities and modes of strength and endurance exercises was carried out by de Souza et al (2007). The modes of aerobic exercises were either continuous (5 km run at 90% of AT) or intermittent (1:1 minute at VO_{2max}) and the upper and lower body strength exercises for maximum intensity were set at 1RM and strength endurance at 80% of 1RM. The results showed that the intermittent endurance run caused a significant decrease in strength endurance performance, however, maximum strength was not affected by either mode of endurance exercise. It was concluded that the intermittent endurance run attenuated strength endurance performance due to peripheral fatigue. These results are in agreement with the "zone of interference" effect and suggests that the degree of the acute interference on strength performance in concurrent training may be dependent on the intensity and volume of strength and endurance exercises performed. Although de Souza and colleagues (2007) demonstrated that a relationship existed between intensity of endurance exercise and the degree of interference on high and low intensity strength training performance, the effect of changes in the intensity of strength training on endurance performance was not examined. Given that endurance exercises involves repetitive sub-maximal contractions, the magnitude of residual effect from strength to endurance training sessions may be influenced by the intensity of the preceding strength training session.

A study conducted by Deakin (2004) investigated different intensities of strength training on endurance performance. The participants in the study either performed high intensity (6RM) or low intensity (6 sets of 20 repetitions) lower body strength exercises of 4 sets and conducted a cycling efficiency test three hours post strength training. The results showed a greater physiological cost during the efficiency test following high intensity compared to low intensity strength training. Although the proposed "zone of interference" effect by Docherty et al (2000) may have applied to the study by de Souza and colleagues (2007), in which high intensity endurance and low intensity strength training caused the greatest interference, such a phenomenon was not observed from the findings by Deakin (2004) since high intensity strength training caused the most profound interference in endurance performance. These differences in results between the study by de Souza et al (2007) and Deakin (2004) suggests that the degree of interference in relation to the intensity of the exercise may be dependent on the mode of exercise (i.e. strength or endurance training). Subsequently, the examination of both strength and endurance performance appears to be essential when manipulating the intensity of the exercises.

Despite the greatest interference in cycling efficiency following high intensity strength exercises reported by Deakin (2004), the effect that the intensity of strength training has on running performance has not been examined. As mentioned previously, due to differences in the physiological responses between running and cycling (Millet, et al., 2009), would running performance be affected differently if performed following high or low intensity strength training? Furthermore, will the intensity of strength training influence running performance at various running speeds? Chen et al (2009) reported a significant increase in VO_2 at 80– and 90% of VO_{2max}, although no differences were found at 70% of VO_{2max} during a RE test following downhill running. Furthermore, Marcora et al (2007) showed that RE was not affected following repetitive vertical jump exercises, however, time-trial running performance was significantly reduced 24 hours post. These findings suggest that running performance at high intensities may be more susceptible to performance decrements than at lower intensities. Indeed, Chen and colleague (2009) suggested that strength training may have greater deleterious effects on running performance at faster speeds since fast twitch muscle fibres have greater susceptibility to muscle damage. However, the impact of high versus low intensity strength training on running performance at various running speeds has not been examined.

2.7.3. Sequence of Mode of Training

Amongst the concurrent training studies conducted thus far, various sequencing of the exercises has been implemented with strength before endurance training (Balabinis, et al., 2003; Bell, et al., 2000; Dolezal & Potteiger, 1998; Häkkinen, et al., 2003) and endurance before strength training (Glowacki, et al., 2004; Leveritt, et al., 2003; McCarthy, et al., 2002). The findings from these studies suggest that the combination of strength and endurance exercises in the one training regime impairs strength development with minimal interference in endurance adaptations. The similarities in the findings from these previous studies suggest that concurrent training can attenuate strength development despite different sequencing of strength and endurance exercises. However, since the order of strength and endurance exercises were not alternated within the one study, the methodology used by these previous studies do not elucidate the true extent of the effects the sequence of the exercises have on adaptation. To date, there have only been a limited number of concurrent training studies that have directly examined the sequence of the mode of training (Chtara, et al., 2008; Gravelle & Blessing, 2000; Silvers & Dolny, 2011).

The earliest study investigating the physiological adaptation following different sequences of the mode of training was conducted by Collins and Snow (1993). The participants in this study were allocated into groups that performed strength prior to endurance training (SE) and groups that performed endurance prior to strength training (ES). Strength and endurance assessments (1RM and VO_{2max} test, respectively) were carried out 7 weeks following the commencement of the prescribed concurrent training program. The participant's VO_{2max} significantly increased for both groups (SE and ES); however, there were no significant differences between the groups. Similarly, both groups significantly increased 1RM from pre– to post training and no differences were found between the groups except for the shoulder press exercise where the ES group was significantly greater than the SE group. Although 1RM was found to be different for the shoulder press exercise between the groups, as the other three strength exercises showed no differences in 1RM, the authors concluded that training sequence had minimal impact on strength and endurance adaptations.

A more recent study conducted by Gravelle and Blessing (2000) compared groups performing rowing followed by strength training, strength training followed by rowing and an ST group. The results showed that 1RM strength was not affected between the groups, however, a significant increase in VO_{2max} following 11 weeks of training was observed for the group that performed rowing followed by strength training and the ST group but not the group that performed strength training followed by rowing. This demonstrates that the sequence of the mode of training does not affect the development of strength; although interference for endurance adaptations may occur if endurance preceded strength training. However, Chtara et al (2005) showed significantly greater improvements in 4 km running time trial performance for the ES group compared to the SE group that undertook concurrent training for 12 weeks. Further, Chtara et al (2008) examined the effects of the sequence of high-intensity endurance and circuit training on muscular strength and anaerobic power. The results showed no significant differences in 1RM strength and anaerobic power between the SE group and ES group.

From the results obtained by Collins et al (1993), Gravelle et al (2000) and Chtara et al (2008), it appears that the sequence of the mode of training in a concurrent training program may not affect strength adaptations. However, contradictory findings were evident between Gravelle et al (2000) and Chtara et al (2005) where endurance adaptations were attenuated when endurance preceded strength compared to when strength preceded endurance training, respectively. Although suggestions to the possible reasons for the endurance adaptations specific to the sequence of the mode of exercises were not given by the authors, differences in the study design (i.e. male vs. female participants; rowing vs. running; circuit vs. explosive type training; both modes of exercises performed within the one session vs. multiple days) may have caused disparity in the results between the two studies. One approach to determine the mechanisms contributing to the effect that the sequence of the mode of exercises has on endurance adaptation may be to examine the acute residual effects of the sequence of the mode of training on endurance performance.

A study conducted by Drummond, Vehrs, Schaalje and Parcelln (2005) examined the acute aerobic response of strength and endurance training sequence by measuring peak oxygen consumption and excess post exercise oxygen consumption (EPOC). The participants in this study completed running only, strength training only, strength training followed by running and then running followed by strength training in the one session, respectively. The results showed that EPOC was greater when running preceded strength training compared to when strength preceded running. Since the running protocol was conducted at a low intensity (i.e. 70% of VO_{2max}), the authors postulated that EPOC may have been less when strength training preceded running since the running protocol may have accelerated recovery following strength training. Although this study demonstrated that EPOC was affected as a result of the sequence of strength and endurance training, measures were based on metabolic conditions at rest.

A study conducted by Deakin (2004) investigated the acute effects of strength and endurance training sequence on muscle force generating capacity and sub-maximal cycling performance. The participants in this study either performed strength training prior to cycling (SC) or strength training followed by cycling in random order (CS). A cycling efficiency test was also conducted three hours following the second training session and knee-extension MVC assessments were carried out prior to each training session and the cycling efficiency test. The results showed similar reduction in knee-extension torque following the strength session of the SC and CS sessions. However, the cycling session of the SC session showed a greater reduction in knee-extension torque than the CS session. Results of the cycling efficiency test revealed greater physiological cost following SC compared to the CS sessions. Subsequently, it was concluded that strength and endurance performance was impaired to a greater extent with SC compared to CS. This demonstrates that the recovery dynamics and the physiological responses following training sessions are affected by the sequence of the mode of training and the type of exercise in which strength and endurance indices were measured.

The aforementioned studies have shown that acute responses to the altered sequence of the mode of training are affected with both cycling and running exercises (Deakin, 2004; Drummond, et al., 2005). Although Drummond and colleagues (2005) exemplified changes in EPOC in response to the altered strength and endurance training sequence, endurance performance was not examined. The study carried out by Deakin (2004) examined both the acute strength and endurance parameters in response to changes in the sequence of the mode of training; however, running was not incorporated in the investigation. Thus, will there be a greater impact on the acute responses to the sequence of the mode of training on running performance if running was sequentially altered with strength training given that running has been suggested to exhibit greater energy expenditure than cycling at the same intensity (Millet et al., 2009)? Furthermore, Deakin (2004) incorporated a three hour recovery period between strength and endurance training sessions and examined the sequence effect on cycling performance on the same day. If the duration between the two modes of exercises were separated by more than three hours, will the alteration in the sequence of the mode of training still have an effect on endurance performance? And will this effect be carried forward to the next day?

2.7.4. Duration between the Modes of Training

Producing concurrent training programs may appear to be a challenging task given that various modes of exercises are incorporated with a wide spectrum of training variables. The variation in rest periods between the modes of exercises may be one contributing factor to this ambiguity of the nature of concurrent training. For example, exercise programs can be considered as concurrent training if strength and endurance exercises are performed with several minutes to several hours apart or performed on alternating days. However, concurrent training programs with varying durations between the modes of exercises are not the same since the recovery dynamics and the subsequent degree of interference on either strength or endurance adaptation would differ. It has been suggested that susceptibility to sub-optimal training adaptations may be the result of insufficient recovery periods between strength and endurance training sessions (Craig, et al., 1991).

The rest periods between the modes of exercises in previous concurrent training studies have varied substantially. For example, concurrent training studies with durations of 10-15 minutes (Chtara, et al., 2008; Gravelle & Blessing, 2000; Nelson, et al., 1990) to 5-6 hours (Kraemer, et al., 1995) between strength and endurance training sessions have shown attenuation in endurance, strength and/or power development. Assumptions can be made that studies that have performed both strength and endurance exercises on the same day would cause a greater interference in strength and/or endurance adaptations compared to alternating days due to limited duration of recovery (Leveritt & Abernethy, 1999). However, a greater number of concurrent training studies incorporating strength and endurance exercises on alternating days have been shown to impair strength (Bell, et al., 2000; Gergley, 2009; Putnam, et al., 2004), endurance (Dolezal & Potteiger, 1998; Glowacki, et al., 2004), torque production (Dudley & Djamil, 1985) and power development (Häkkinen, et al., 2003; Izquierdo, et al., 2004). In addition, studies in which strength and endurance exercises were performed on the same day have also shown been found to enhance strength and endurance development (Ferketich, et al., 1998; Shaw & Shaw, 2009; Wood, et al., 2001).

According to the above-mentioned studies, it would appear that the duration between the modes of exercises is unrelated to the extent– and type– of adaptation in response to concurrent training. However, the disparity in results between concurrent training studies is often due to differences in research design, training methodology and assessment protocols.

In addition, since systematic investigations of altering the duration between strength and endurance training sessions is limited, it would be premature to conclude that variation in recover periods between modes of training sessions are independent of the extent and type of concurrent training adaptation.

A study conducted by Sale et al (1990) compared the responses of performing strength and endurance training on the same day to performing strength and endurance training on alternating days. The concurrent training program consisted of two high volume (i.e. 6-8 sets of 15-20RM of leg press exercises) strength sessions and two high intensity (i.e. 6-8 intermittent bouts at 90-100% of VO_{2max}) endurance training sessions per week. One group performed strength and endurance training on alternating days whereas the other group performed strength and endurance training in the one session. In addition, the sequence of the mode of exercises was altered between the two days of training for the group that performed strength and endurance exercises on the same day (i.e. endurance training preceded strength training on the first day whereas strength training preceded endurance training on the second day). The results showed that strength development (i.e. 1RM leg press) was significantly greater for the group that performed the two modes of training sessions on alternating days. However, citrate synthase concentration was significantly greater for the group that performed the two modes of training sessions on the same day although no between-group differences were found for VO_{2max}.

In light of the findings by Sale et al (1990), interference in strength development appears to occur as a result of performing strength and endurance training sessions on the same day, indicating that recovery period may have an effect on concurrent training adaptation. The authors postulated that sub-optimal strength adaptations may have been induced because the quality of the strength training session was impaired as it was performed following endurance training sessions. However, the increase in citrate synthase concentration indicates that the combination of strength and endurance training on the same day may accelerate endurance adaptations. Given that VO_{2max} tests were the only endurance performance measures incorporated, Sale and colleagues (1990) suggested that endurance protocols consisting of longer durations at sub-maximal intensities may have exemplified improvement in endurance for the group that performed strength and endurance training sessions on the same day. Subsequently, it appears that endurance performance measures at various running speeds should be incorporated in acute and chronic concurrent training studies to assist in generating findings that are more applicable.

Whilst Sale and colleagues (1990) postulated potential endurance benefits by performing strength and endurance exercises on the same day as a result of an increase in citrate synthase concentration, the sequence of the mode of exercises was altered between the two days of training. Chtara et al (2005) altered the sequence of the modes of training on the same day and showed that 4 km running time trial performance was significantly less for the SE group compared to the ES group. Chtara and colleagues (2005) suggested that the accumulation of residual effects of fatigue from strength to endurance training sessions may have limited optimal endurance development. If strength training had preceded endurance training on the same day as opposed to alternating days, different enzymatic activities may have been found during the study by Sale et al (1990). In addition, Sale et al (1990) incorporated cycling whereas Chtara et al (2005) prescribed running for endurance training. Given that the movement executed during cycling mimics that during the performance of leg-press exercises as described in the study by Sale et al (1990), alterations in oxidative enzymatic reactions would be expected.

Another factor contributing to the disparity in results between Chtara et al (2005) and Sale et al (1990) may be the differences in strength training protocols. The strength training session in the study by Sale et al (1990) consisted of 6 sets of 15-20 repetitions of leg press exercises with the first three sets performed at 50–, 70– and 90% of 15-20RM and the latter three sets to failure using concentric contractions. In contrast, Chtara et al (2005) incorporated strength training exercises in a periodised manner commencing with high volume strength training (15-20RM) at a self-selected pace to explosive strength training exercises (e.g. drop jumps, leg hops). A number of reports have shown that fast– compared to slow– eccentric contractions impaired muscular performance to a greater extent and induced a higher level of EIMD (Chapman, et al., 2006; Chapman, et al., 2008). Subsequently, explosive exercises which require fast eccentric contractions may have contributed to the interference of endurance development in the study by Chtara et al (2005) as opposed to the concentric-focused strength training protocols implemented by Sale et al (1990).

Given that the magnitude of training stimuli is dependent on the training variables employed (e.g. intensity, volume, mode of exercise) (Kraemer, et al., 2002), the nature of the strength training protocols would induce various types of physiological responses which may affect the amount of recovery period necessary to limit its impact on subsequent endurance training sessions. Indeed, resistive-type exercises have been shown to cause neuromuscular fatigue immediately following to 96 hours post (Kawakami, et al., 2000; Lentz & Nielsen, 2002; Sargeant & Dolan, 1987), muscle glycogen depletion immediately following to 6 hours post (Deakin, 2004) and EIMD from as early as 8 hours to 72 hours post (Jakeman, Byrne, & Eston, 2010; Tokmakidis, et al., 2003). Subsequently, various physiological mechanisms can contribute to attenuation of endurance performance depending on the nature of the strength training protocol. Deakin (2004) reported that a high intensity strength training session (i.e. 6RM) induced a greater physiological cost during sub-maximal cycling than a low intensity strength training session (i.e. 20RM) three hours post. Furthermore, a significant reduction in MVC three hours post was found only for the high intensity strength training session. These findings suggest that high intensity strength training impaired the neuromuscular function to a greater degree than low intensity strength training which may have contributed to attenuation in endurance performance. However, the recovery periods between the strength training sessions and subsequent endurance performance assessments were standardized to three hours in the study by Deakin (2004). Furthermore, the endurance performance measures were limited to cycling.

In order to determine the effect of recovery periods between different modes of training sessions in response to concurrent training, it is essential to examine the acute effect of altering the duration between strength and endurance trainings sessions. Palmer et al (2001) systematically examined the effect of strength training on RE 1–, 8– and 24 hours post and found that RE was impaired 1– and 8 hours post but unaffected 24 hours post. Subsequently, it was concluded that 24 hours was sufficient to perform sub-maximal running without residual effects from a preceding strength training session. However, running performance was assessed at a single intensity and was limited to sub-maximal efforts. To date, the impact of altering the recovery periods between strength and endurance training sessions consisting of high intensity strength training exercises on subsequent running performance at various running speeds remains unclear.

2.7.5. Strength Training Contraction Velocity

In addition to recovery periods between strength and endurance training sessions, strength training contraction velocity may be one training variable that affects endurance training sessions following strength training and subsequently may impact endurance adaptations in response to concurrent training. Indeed, alterations in contraction velocity have been associated with changes in neural (Häkkinen, Alen, & Komi, 1985), hypertrophic (Housh, Housh, Johnson, & Chu, 1992) and metabolic (Ballor, Becque, & Katch, 1987) responses following strength training. Accordingly, the physiological systems experience various stresses that may be dependent on contraction velocity during strength training and subsequently impact training adaptation. The slow contraction velocities can be defined by two models: unintentional– and intentional– slow contractions (Kraemer, et al., 2002). The unintentional slow contractions are executed due to an inability to perform fast contractions because of exercises being performed against heavy resistances. This notion follows that the products of force and velocity are inversely related, thereby preventing muscles to contract at high speeds during high intense strength training exercises which necessitate greater muscular force production. On the other hand, slow contraction velocities can be intentional by deliberately slowing the execution of a movement against an external load.

Kraemer et al (2002) suggested that sub-maximal loads are used during the performance of strength training exercises with slow contractions in order to obtain greater control of body movement velocity. Indeed, a study has shown that concentric force production was significantly less during a bench press exercise performed with intentionally slow contractions (Keogh, Wilson, & Weatherby, 1999). Subsequently, strength training exercises performed with slow concentric– and eccentric contractions may limit detrimental effects on subsequent endurance performance. However, Keeler et al (2001) reported that a 30% reduction in training load was required during super-slow (10 seconds concentric: 5 seconds eccentric) contractions compared to slow (two seconds concentric: four seconds eccentric) contractions which resulted in significant less strength gains after 10 weeks of training. These findings indicate that optimum strength gains may not occur with slower contraction velocities during strength training.

Performing strength training exercises with fast concentric (i.e. one second) and slow eccentric contractions (i.e. four seconds) may ensure adequate training stimuli for strength development whilst limiting its attenuating effect on the quality of subsequent endurance training sessions. The morphological properties of the muscle have greater susceptibility to neuromuscular fatigue and muscle damage during eccentric– compared to concentric– contractions (Lavender & Nosaka, 2006; Muthalib, Lee, Millet, Ferrari, & Nosaka, 2010). It has been suggested that the lengthening mechanisms of the muscular contractile properties causes damage to sarcomeres and components of the excitation-contraction coupling system (Morgan & Allen, 1999; Proske & Morgan, 2001). In light of this hypothesis, Chapman et al (2006) showed that DOMS and CK were significantly greater whilst MVC was significantly lower following fast– compared to slow– eccentric contractions for up to 168 hours post.

Similarly, Chapman et al (2008) showed that fast– compared to slow– eccentric contractions induced significant reductions in isometric– and concentric– MVC and joint range of motion and significantly increased CK and DOMS. Accordingly, slow eccentric contractions appear to limit factors that impair muscle function to a greater extent than fast eccentric contractions. However, exercises incorporated by Chapman et al (2006; 2008) did not consist of concentric contractions which are an essential component of movement execution during strength training exercises. Furthermore, these exercises were performed using isokinetic devices, which are not true indications of traditional strength training exercises.

A study conducted by Dolezal et al (2000) examined the impact of performing incline leg press exercises with fast concentric– (i.e. one second) and slow eccentric– (i.e. four seconds) contractions on EPOC. The results showed that resting metabolic rate was significantly elevated up to 48 hours post exercise for strength –trained and –untrained individuals. Similarly, Hackney et al (2008) reported a significant increase in resting metabolic rate 24 and 48 hours following a strength training session consisting of upper and lower body exercises performed with fast concentric (i.e. one second) and slow eccentric (i.e. three seconds) contractions amongst strength –trained and –untrained individuals. Whilst these findings suggest that traditional strength training exercises performed with fast concentric– and slow eccentric– contractions increases metabolic rate 24-48 hours post, the measures were limited to metabolic conditions at rest. In addition, although resting metabolic rate appears to increase regardless of strength training type, the acute responses of lower body only (Dolezal et al., 2000) and whole body (Hackeny et al, 2008) strength training sessions were analysed by two different studies. Deakin (2004) showed that different volume of strength training methods (e.g. lower body only versus whole body strength training) significantly altered the physiological cost of cycling. However, this study incorporated strength training exercises at a self-selected pace. To date, the impact of altering strength training volume with fast concentric– and slow eccentric– contractions on endurance performance have received little attention.

2.7.6. Duration of the Training Studies

The training duration within the concurrent training studies conducted thus far have varied from as short as 7 weeks (Glowacki et al., 2004) to as long as 22 weeks (Sale et al., 1990). Whilst these concurrent training studies have been shown to either develop or interfere with strength and/or endurance adaptations, the progressions of the physiological adaptations that occur during the training program are unknown. Subsequently, in order to examine the physiological processes that contribute to induce or interfere with training adaptation in response to concurrent training, strength and endurance assessments must be undertaken regularly throughout the training program. Several concurrent training studies have conducted physiological tests midway through and then following the training program and have found differences in the nature of the development of strength and endurance between the ST group, the END group and the CON group (Bell et al., 2000; Glowacki et al., 2004; Izquierdo et al., 2004; Nelson et al, 1990).

A study conducted by Glowacki et al (2004) compared the outcomes of concurrent training between the ST group, the END group and the CON group. Strength assessments were conducted prior to the commencement of training and then again at weeks 6 and 12. The results showed significant increases in peak oxygen consumption for the END group although no significant increases were found for the ST group and the CON group for weeks 6 and 12. For the strength assessment, there were no significant differences in bench press 1RM between the ST group and the CON group at week 6; however, the bench press 1RM was significantly greater for the ST group compared to the CON group at week 12. Similarly, Bell et al (2000) investigated the effects of 12 weeks of concurrent training and found a similar increase in VO_{2max} for the ST group and the CON group at weeks 6 and 12. For the strength assessment, there were no significant differences in leg press 1RM between the ST group and the CON group at week 6 of concurrent training; however, significantly greater for the ST group compared to the CON group at week 12.

An extended study conducted by Izquierdo et al (2004) examined the effects of 16 weeks of concurrent training on strength and endurance development. The results showed that the significant increase in the maximal workload attained during a discontinuous incremental cycling test were similar at weeks 8 and 16. In response to strength training, no differences were found in 1RM squats between the ST group and the CON group at week 8; however, the ST group was significantly greater than the CON group at week 16. Similarly, Häkkinen et al (2003) found that the rate of force development significantly increased for the ST group at week 11 compared to pre-training condition and significantly increased at week 21 compared to week 11 of training. For the CON group, the rate of force development significantly increased at week 11 compared to pre-training conditions, however, significantly decreased at week 21 compared to week 11 of training. The VO_{2max} for the CON group significantly increased at weeks 11 and 21; however, the endurance development could not be compared between groups as an END group was not incorporated in the study.

Contrary to the studies demonstrating a gradual decline in strength development, findings by Nelson (1990) showed that the development of strength between the ST group and the CON group were similar throughout a 20 week concurrent training program. However, different patterns in the development for endurance were found between the END group and CON group. The VO_{2max} significantly increased for the CON group at week 11, although further endurance development did not occur by week 20. For the END group however, the VO_{2max} significantly increased at weeks 11 and 20. Collectively, these studies demonstrate that the development of strength, power and endurance is enhanced during the early phase of concurrent training, however, appears to be interfered during the latter phase of training for the CON group. This is evident as the studies showed that the adaptations respective to the ST group and the END group were enhanced throughout the training program. However, the development of strength, power and endurance for the CON group deteriorated progressively.

Interestingly, Gravelle et al (2000) examined the effects of altering the sequence of rowing and strength training in an 11 week concurrent training program. The results showed that leg press strength was significantly increased for participants that performed rowing prior to strength training, strength training prior to rowing and participants in an ST group when assessed at the middle and following the training program. However, when the strength indices were compared from mid– to post training, the significant increase in leg press 1RM was only found in the group that performed rowing prior to strength training and the ST group. This exemplifies that the timing in which adaptations occur may not only be dependent on the modes of exercises, but also associated with the alteration of the training variables (i.e. the sequence of the mode of training). In addition, this study showed that the investigation of strength development midway through and then following the training program is crucial in order to determine the physiological processes that occur throughout training. If Gravelle and colleagues (2000) only conducted strength assessments pre– and post– training, a method commonly used by other concurrent training studies, then the authors may not have been able to ascertain the significant effects of the sequence of the mode of training on adaptations.

2.7.7. The Accumulation Effect of Strength and Endurance Training

Whilst concurrent training studies have found that the onset of an adaptation may vary depending on the mode of exercise and training variables employed (Glowacki et al., 2004; Gravelle et al., 2000; Izquierdo et al., 2004; Nelson et al., 1990), the type of acute responses that occur during a concurrent training program is still unknown. Given that the type of adaptation is dependent on the accumulation of acute responses (Baar, 2006), the mechanisms to the type and extent of training adaptation cannot be understood simply by conducting physiological assessments prior to–, mid– and following a concurrent training program. One approach of determining the physiological processes and the subsequent adaptation induced as a result of concurrent training may be to systematically examine the acute interaction between strength and endurance training using various performance measures.

Numerous studies examined the impact of endurance exercises on muscle force generation capacity and have shown reduction in MVC 6 hours following 60 minutes of cycling (Bentley et al., 1998; Bentley et al., 2000) and 24-48 hours following long distance running (Millet, Millet, Hofmann, & Candau, 2000; Millet, et al., 2002). However, there has been limited investigation of the effects of traditional strength training on endurance performance. Palmer et al (2001) showed that whole body strength training sessions significantly increased the physiological cost of sub-maximal running 1– and 8 hours post. These findings suggest that endurance training stimuli may be impaired with insufficient recovery between strength and endurance training sessions. Whilst Palmer et al (2001) examined the impact of strength training on RE on the same day (i.e. 1– and 8 hours post) and over two days (i.e. 24 hours post), the endurance performance measures were collected following a single strength training session. Subsequently, it is difficult to generate appropriate assumptions regarding potential effects that strength training may have on endurance adaptation given that concurrent training programs consist of multiple training sessions of both strength and endurance exercises. In order to have a better understanding of the cause and effect of concurrent training on endurance adaptation, it is essential to examine acute responses over multiple strength and endurance training sessions.

Drummond et al (2000) compared EPOC following a session consisting of both strength and endurance exercises to when strength and endurance exercises were performed in isolation. The results showed that EPOC was greater following the combination of strength and endurance exercises compared to when strength and endurance exercises were performed alone. Drummond and colleagues (2000) suggested that the combination of strength and endurance exercises may have generated greater physiological responses due to a large amount of work accumulated. However, the metabolic condition following strength and endurance training sessions were measured at rest. Deakin (2004) examined the impact of the sequence of strength and endurance training on cycling efficiency. Specifically, strength and endurance training sessions were separated by three hours and cycling efficiency was conducted three hours following the last training session on the same day. The results showed that the physiological cost of cycling was greater when strength training preceded endurance training although no effect was found with the reverse sequence. This tends to suggest that fatigue generated by strength training could be augmented due to subsequent endurance training sessions. However, Deakin (2004) examined the acute effects strength and endurance training sessions on endurance performance on the same day. It is unknown whether strength and endurance training sessions performed over multiple days will generate cumulative effects of fatigue.

Chen and Hsieh (2001) examined the effects of performing isokinetic eccentric contractions of biceps brachii over 7 consecutive days on muscle force generation capacity and muscle damage. The results showed that maximal isometric force was significantly reduced during the 7 day period. Furthermore intra-muscular enzymes (i.e. CK and lactate dehydrogenase) and muscle soreness were significantly increased during days 3-6. These results suggest that 24 hours recovery between eccentric training sessions is insufficient and will impair the morphological properties of the muscle. In addition, the report by Chen et al (2001) exemplifies what could be observed during a microcycle of a strength training program if strength training exercises for the same muscle groups were performed over consecutive days. According to the findings by Chen et al (2001), the quality of strength training sessions may be compromised and thus impair strength development by undertaking a program consisting of daily strength training sessions targeting the same muscle groups.

Consequently, it is recommended that strength training sessions be performed two to four days per week with at least 48 hours recovery between training sessions in order to optimize strength–, hypertrophic and strength endurance adaptation (Kraemer et al., 2002). In contrast, endurance training sessions are commonly prescribed over consecutive days for endurance athletes aiming to improve aerobic endurance (Faude, et al., 2009). Subsequently, the recovery periods between training sessions may be dependent on the mode of exercise. However, there is minimal knowledge regarding the recovery dynamics between strength and endurance training sessions when performed concurrently over multiple days. Given that the combination of strength and endurance training has been shown to increase EPOC (Drummond et al., 2000) and physiological cost of cycling (Deakin, 2004) on the same day, endurance performance may be consistently impaired by performing strength and endurance training sessions over a week (i.e. a microcyle of a concurrent training program). To date, the effect of alternating-day strength training performed in conjunction with consecutive-day endurance training on running performance has not been examined. Such investigation will enhance the understanding of fatigue– and recovery dynamics between and following strength and endurance training sessions during concurrent training.

2.7.8. Summary

According to the findings from the studies thus far, the mechanisms of the interference in strength development as a result of concurrent training has been attributed to attenuation in an increase in muscle fibre CSA, deactivation of cell signalling pathways essential for protein synthesis, and alterations in muscle fibre type. Sub-optimal endurance adaptations as a result of concurrent training have been suggested to be caused by a reduction in oxidative enzymes, mitochondrial volume, and alterations in muscle fibre type. Despite these hypotheses, the mechanisms and the degree of interference in training adaptation as a result of concurrent training appears to be inconclusive. This may be due to differences in the training methods used by each study given that the acute response of each training program is dependent on the type of training variables (e.g. mode of exercise, training intensity, sequence of the mode of training, and contraction velocity) employed. For example, a concurrent training program that incorporates training variables that induces greater fatigue from one training session to the next may cause substantial interference in strength and endurance development as opposed to a concurrent training program that generates lesser fatigue. However, to date, there is very little evidence of the acute effects of strength and endurance sessions on various performance parameters. Such findings will provide health professionals an understanding of the body's acute sensitivity to particular training methods as well as an indication of the mechanisms attributing to the type of adaptation induced during and following concurrent training. Subsequently, it is essential to systematically examine the acute responses of combining strength and endurance training sessions in various ways.

Chapter 3

The reliability of running economy among trained distance runners and field-based players

Doma, K., Deakin, G. B., Leicht, A. S., & Sealey, R. M. (2012). The reliability of running economy among trained distance runners and field-based players. *Journal of Exercise Science and Fitness,10*(2), 90-96.

3.1 Introduction

The common method of assessing whether strenuous training sessions attenuate running performance in a randomized controlled trial is a RE test (Saunders, et al., 2004a). The RE test has a high reliability (Saunders et al., 2004b) and a strong relationship to long distance running performance (Conley & Krahenbuhl, 1980; Costill, 1967; Di Prampero et al., 1993). A few studies have shown that RE was attenuated following down-hill running (Chen et al. 2007; Chen et al., 2009), suggesting that the quality of a subsequent endurance training session may be compromised. However, a greater number of studies have reported that RE is not affected several hours following strenuous exercises (Marcora & Bosio, 2007; Paschalis, et al., 2005; Scott, et al., 2003; Vassilis et al., 2008). Subsequently, findings from these studies indicate that bouts of running sessions can be carried out with minimal detriment in performance. However, given that RE tests are conducted under AT for only 10-20 minutes (Saunders, et al., 2004a), drawing conclusions on running performance in response to strenuous exercises solely based on RE may be premature. In fact, a report has shown that running sprint ability is impaired 48 hours following repeated counter movement jumps

(Twist & Eston, 2005). These findings demonstrate that the sensitivity to detect changes in running performance may in part be dependent on the intensity of running.

Incorporating running at maximum effort as well as RPE in a RE test would improve the versatility of the protocol and broaden the interpretation of running performance following various experimental interventions. For example, Scott et al (2003) found that RE was not affected 24-30 hours following lower extremity resistance exercises although RPE did increase during sub-maximal running. Marcora and Bosio (2007) also found that RE was not affected 48 hours following repeated vertical jump despite increases in CK and muscle soreness. However, the results showed that time-trial performance (TTP) worsened and that RPE was greater during sub-maximal running due to EIMD. Collectively, these findings demonstrate that strenuous exercise increases perception of effort at sub-maximal running and attenuates running performance at maximum effort. However, had Scott and colleagues (2003) and Marcora and Bosio (2007) not incorporated performance parameters other than RE, their findings would have led to alternative conclusions. Subsequently, RE tests may become more robust by incorporating RPE and running performance measures at maximum effort.

The TTP is reliable and effective as a complementary test protocol to a RE test (Laursen, Francis, Abbiss, Newton, & Nosaka, 2007; Schabort, Hopkins, & Hawley, 1998). However, the usability of such a protocol conducted at the completion of a RE test is questionable as it would require the runner to alter the running speed by hand which would affect the economy of running unless a non-motorized treadmill is used. In addition, TTP would require further familiarity sessions due to complications associated with the setting of running speed. Time-to-exhaustion (TTE) may be a better indicator for running performance to maximum effort when conducted at the completion of a RE test as the running speed is maintained during the protocol and the intensity would be identical between testing sessions. However, the reliability of RE at various intensities with a TTE protocol has not been examined as far as the authors are aware.

Studies have shown that RE is highly reliable amongst small homogenous samples (n = 4-8) of elite runners or moderately trained runners (Billat, Renoux, Pinoteau, Petit, & Koralsztein, 1994; Morgan et al., 1994; Pereira & Freedson, 1997). However, homogenous samples are often not available and the practicality of such findings is limited to that specific cohort. Heterogeneous cohorts would allow access to a greater sample and provide research outcomes that can be applied to a wider demographic, but may result in high inter-individual variability. Ways to minimize this variability of RE is to quantify the C_R expressed relative to body mass raised to the power of 0.75 per meter (VO_2 mL.kg$^{-0.75}$.m^{-1}). For example, Helgerud (1994) reported standard deviations of ~±8% when C_R was expressed relative to body mass (VO_2 mL.kg^{-1}.min^{-1}) whereas ~±5% was found amongst junior soccer players (Helgerud, Engen, Wisloff, & Hoff, 2001) and trained distance runners (Helgerud, Storen, & Hoff, 2010) when expressed in VO_2 mL.kg$^{-0.75}$.m^{-1}. Whilst RE expressed as absolute VO_2 (mL.min^{-1}) (Morgan, et al., 1994) and relative VO_2 (mL.kg^{-1}.min^{-1}) (Pereira & Freedson, 1997) is reliable, little is known about the reliability of C_R.

The purpose of the current study was to determine whether RPE and TTE are reliable when collected in conjunction with a RE test and to determine the reliability of C_R at varying speeds amongst a heterogeneous cohort (i.e. trained and moderately endurance trained runners).

3.2 Methods

Participants

Seven trained male runners and 7 moderately endurance trained males (METM) participated in the study (**Table 3.1**). The trained runners (TR) were middle to long distance runners (1500-10,000 m) who had all run a 10,000 m time trial faster than 37 minutes during the last 6 months and they were all running at least 50 $km.week^{-1}$ for the duration of the study. The METM had various sporting backgrounds (e.g. soccer, basketball and cricket) and were covering approximately 5-10 $km.week^{-1}$. Each participant completed informed consent before taking part in any testing procedures. All procedures in this study were approved by the Institutional Human Research Ethics Committee and were run in accordance with the Declaration of Helsinki.

Table 3.1. Physical characteristics of the trained and moderately endurance trained runners

Variables	TR (n = 7)	METM (n = 7)
Age (years)	22 ± 4	23 ± 2
Height (m)	1.79 ± 0.09	1.82 ± 0.06
Mass (kg)	71.4 ± 8.5	75.8 ± 6.6
VO_{2max} (mL.kg^{-1}.min^{-1})	69.42 ± 2.60	58.61 ± 3.23†
70% VT_2 (km.h^{-1})	11.64 ± 0.64	8.57 ± 1.25†
90% VT_2 (km.h^{-1})	14.93 ± 0.75	11.92 ± 1.22†
110% VT_2 (km.h^{-1})	18.31 ± 0.88	15.27 ± 1.42*
%VO_{2max} @ VT_2	88.29 ± 6.70	79.71 ± 4.03*
TTE (s)	336 ± 119	253 ± 88

Values are mean ± SD

TR = trained runners, METM = moderately endurance trained males, (VO_{2max} = maximal oxygen uptake, VT_2 = ventilatory threshold 2, %VO_{2max} @ VT_2 = percentage maximal oxygen uptake at ventilatory threshold 2, TTE = time to exhaustion from RE test

**P* < 0.05, †*P* < 0.01 values significantly different from trained runners

Research design

Following a familiarization session, the participants were tested over three separate sessions. A VO_{2max} test was conducted in the first session and the last two sessions each consisted of an identical RE test. The second ventilatory threshold (VT_2) was determined during the VO_{2max} test in order to ascertain the speed at which the participants ran during the RE tests. At least one day of recovery between the VO_{2max} test and RE test and a minimum of 2 days and a maximum of 5 days of recovery between the two RE tests were provided, as it has been suggested that more than one day between repeated measures may be required to pre-empt bias from inadequate recovery (Atkinson & Nevill, 1998). Technical and biological variations were controlled by calibrating all measurement equipment, requiring participants to maintain their training intensity and volume during the course of the study, participants wearing the same shoes for every test, refraining from high intensity physical activity for at least 24 hours prior to testing and refraining from caffeine–, food– and supplement intake for at least 2 hours prior to testing.

Maximal oxygen consumption test

Prior to the VO_{2max} test, a progressive warm-up was completed by walking at 5 km.h^{-1} for 5 minutes then jogging at 8–,10–, and 12 km.hr^{-1} for 1 minute, respectively, at a continuous pace on a treadmill (Quinton Q65, USA). The VO_{2max} test involved continuous incremental running in stages starting at 12 km.h^{-1} and increasing the speed by 1.5 km.h^{-1} every minute until exhaustion. The gradient was maintained at 0% throughout the test. This particular VO_{2max} test was deemed appropriate for the current participants given that it was used on a similar endurance trained cohort (Doma, Deakin, & Sealey, 2012). Heart rate (Polar RS800, New York, USA) and RPE (Borg's 6-20 point scale) were recorded every minute. Expired air samples were analyzed with a Cosmed K4b^2 gas analyzer (Cosmed, Rome, Italy). The flow meter was calibrated with a three litre calibration syringe and a reference air calibration of the system was performed using a certified alpha gas mixture of 16% oxygen and 4% carbon dioxide concentration. Data were measured breath by breath and the respiratory variables averaged every 15 s (Sealey, Leicht, Spinks, & Sinclair, 2010). The highest average VO_2 value over a 15 s interval was accepted as VO_{2max} when the participant met three of the four criteria: VO_2 plateau, RPE > 17, respiratory exchange ratio (RER) > 1.1, peak heart rate > 90% of age predicted heart rate (Midgley, McNaughton, Polman, & Marchant, 2007). The VT_2 for each participant was determined by identifying the inflection point of ventilation (V_E) with respect to carbon dioxide production (VCO_2) on a scatter diagram (Neder & Stein, 2006).

Running economy test with time to exhaustion

The warm-up for the RE test was identical to the VO_{2max} test. The RE protocol was a three stage discontinuous incremental test to exhaustion. A two minute passive recovery period was given between each stage. The running speed was set at 70–, 90– and 110% of VT_2 for the three stages, respectively. The duration of the first two stages was set at 10 minutes each and the participants ran until exhaustion during the last stage to determine TTE, which was considered as an additional performance variable in conjunction with the physiological parameters. The VT_2 was used due to its greater reliability (Sealey, et al., 2010) and ability to induce the onset of fatigue earlier than the first ventilatory threshold (VT_1) (Kerr, Spinks, Leicht, Sinclair, & Woodside, 2008). The physiological variables of VO_2, V_E, heart rate (HR) and RER were averaged during the last 5 minutes of each of the first two stages to ensure the participants reached steady-state. Steady-state was defined when the change in VO_2 was <10% (Reeves, Davies, Bauer, & Battistutta, 2004). In addition, VO_2 between the 5^{th} and the 10^{th} minute of each of the first two stages were compared to ascertain any possible existence of VO_2 slow component (Demarie et al., 2001). The physiological variables for the last stage were averaged over the last minute as some participants were unable to run for longer than 5 minutes. The aerobic demand of running was expressed as absolute VO_2 ($L.min^{-1}$), relative VO_2 ($mL.kg^{-1}.min^{-1}$) and C_R ($mL.kg^{-0.75}.m^{-1}$). RPE was recorded one minute prior to the end of the first and second stages. During the third stage, RPE was recorded every 30 seconds and the last RPE prior to exhaustion was then selected as perceived exertion.

Statistical analyses

Measures of centrality and spread are shown as mean ± between-participant standard deviation. All data were analyzed using the Statistical Package for Social Sciences (SPSS, version 18, Chicago, IL). The intra-class correlation coefficient (ICC, SPSS two-way mixed, 95% confidence intervals) was used to assess both systematic and random errors that may affect relative test-retest reliability of the physiological and performance variables. The measurement of absolute reliability was expressed using measurement bias/ratio with 95% limits of agreement (rLOA) (Bland & Altman, 1986). The coefficient of variation (CV, 95% confidence limits) was determined according to an EXCEL spreadsheet (Hopkins, 2009). The relationship between absolute differences and the mean of the variables was positive and therefore data were found to be heteroscedastic (an example depicted in **Figure 3.1**), thus all data were transformed using natural logarithms before calculating rLOA (Neville & Atkinson, 1997). Differences between the two RE trials for all variables and VO_2 between the 5^{th} and 10^{th} minute of the first two stages were analyzed using Paired T-tests whereas between-group differences in the physical characteristics for TR and METM were examined using the Independent T-tests. Statistical significance was established at the 0.05 level.

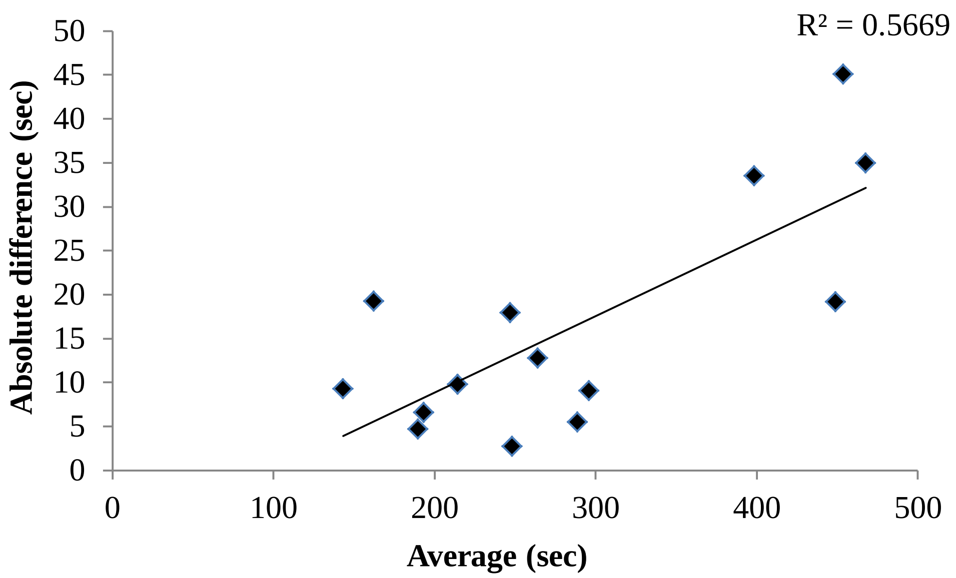

Figure 3.1. Bland and Altman Plot of the absolute difference between trials 1 and 2 against the mean of trials 1 and 2 for time-to-exhaustion demonstrating heteroscedasticity

3.3 Results

The VO_{2max} ($mL.kg^{-1}.min^{-1}$), running speeds at 70–, 90– and 110% of VT_2, and percentage of VO_{2max} at VT_2 were significantly greater for TR than METM ($P < 0.05$) (**Table 3.2**). There were no significant differences in age, height, mass and TTE ($P \geq 0.05$) between TR and METM.

Steady-state VO_2 was achieved within three minutes of the commencement of the first and second stages of Trial 1 and 2. No significant differences were found for VO_2 between the 5^{th} and 10^{th} minute during the first two stages of Trial 1 and 2 ($P \geq 0.05$) with the largest difference being 0.86 mL.kg^{-1}.min^{-1}, eliminating the possible existence of VO_2 slow component.

No significant differences were found for C_R, absolute VO_2, relative VO_2, V_E, VCO_2, RER and HR during stage 1 ($P \geq 0.05$), for C_R, absolute VO_2, relative VO_2, V_E, VCO_2, RER, HR and RPE during stage 2 ($P \geq 0.05$) and during TTE ($P \geq 0.05$) between RE Trial 1 and 2 (**Table 3.2**).Variables that were significantly greater during RE Trial 1 compared to Trial 2 included RPE during stage 1 ($P < 0.05$) and TTE ($P < 0.01$).

Table 3.2. Physiological variables averaged during the last 5 minutes of each of the first two stages and the last minute of the third (time-to-exhaustion) stage of the running economy (RE) test

Variables	RE Trial 1	RE Trial 2	Δ RE Trial 1-2
VO_2 ($L.min^{-1}$)			
First stage	3.34 ± 0.35	3.25 ± 0.28	0.09 ± 0.15
Second stage	4.22 ± 0.53	4.12 ± 0.42	0.10 ± 0.24
Third stage	4.71 ± 0.56	4.61 ± 0.49	0.10 ± 0.18
VO_2 ($mL.kg^{-1}.min^{-1}$)			
First stage	45.25 ± 4.61	44.35 ± 3.59	0.90 ± 0.93
Second stage	56.75 ± 6.86	56.04 ± 6.03	0.71 ± 1.31
Third stage	62.99 ± 7.03	62.31 ± 6.93	0.68 ± 1.10
C_R ($mL.kg^{-0.75}.m^{-1}$)			
First stage	0.75 ± 0.07	0.73 ± 0.06	0.02 ± 0.01
Second stage	0.73 ± 0.06	0.72 ± 0.07	0.01 ± 0.01
Third stage	0.66 ± 0.04	0.65 ± 0.05	0.01 ± 0.01
V_E ($mL.min^{-1}$)			
First stage	76.90 ± 7.73	75.51 ± 7.29	1.39 ± 5.68
Second stage	111.96 ± 13.23	108.63 ± 12.24	3.32 ± 7.78
Third stage	149.20 ± 16.34	149.02 ± 19.30	0.18 ± 10.18
VCO_2 ($L.min^{-1}$)			
First stage	3.10 ± 0.36	3.08 ± 0.29	0.02 ± 0.04
Second stage	4.09 ± 0.60	4.04 ± 0.47	0.05 ± 0.09
Third stage	4.96 ± 0.82	4.88 ± 0.65	0.08 ± 0.12
RER			
First stage	0.94 ± 0.03	0.95 ± 0.04	-0.01 ± 0.06
Second stage	0.99 ± 0.04	1.00 ± 0.05	-0.01 ± 0.07
Third stage	1.06 ± 0.05	1.08 ± 0.07	-0.02 ± 0.09
HR ($b.min^{-1}$)			
First stage	151.64 ± 10.72	149.78 ± 11.04	1.86 ± 6.08
Second stage	176.08 ± 10.37	174.78 ± 9.88	1.30 ± 4.00
Third stage	190.57 ± 9.08	189.74 ± 9.18	0.83 ± 2.69
RPE			
First stage	11.07 ± 1.00	10.57 ± 1.02*	0.50 ± 0.65
Second stage	14.57 ± 1.65	14.86 ± 1.66	-0.29 ± 0.91
Third stage	18.57 ± 1.50	18.79 ± 1.48	-0.22 ± 0.89
TTE (s)			
Third stage	265 ± 113	279 ± 130	13 ± 9.75

Values are mean ± SD

VO_2 = oxygen uptake, C_R = oxygen cost of running, V_E = ventilation, VCO_2 = carbon dioxide production, RER = respiratory exchange ratio, HR = heart rate, RPE = rating of perceived exertion, TTE = time-to-exhaustion

* $P < 0.05$ values significantly different between the first– and second RE trials

The ICC between both trials of each incremental stage of the RE test for absolute VO_2, relative VO_2, C_R, V_E, VCO_2, RER, HR, and RPE ranged from 0.90 to 0.95, 0.93 to 0.96, 0.90 to 0.92, 0.73 to 0.84, 0.64 to 0.78, 0.08 to 0.35, 0.93 to 0.97, and 0.69 to 0.85, respectively (**Table 3.3**). Similarly, the measurement bias ratio for absolute VO_2, relative VO_2, C_R, V_E, VCO_2, RER, HR and RPE ranged from 1.02 to 1.03, 1.01 to 1.02, 1.01 to 1.01, 1.00 to 1.02, 1.01-1.01, 0.98 to 0.99, 1.01 to 1.03, and 0.98 to 1.06, respectively. The CV for absolute VO_2, relative VO_2, C_R, V_E, VCO_2, RER, HR and RPE ranged from 2.4 to 3.1, 2.2 to 2.9, 2.2 to 2.9, 4.8 to 5.3, 4.9 to 7.9, 4.2 to 6.1, 0.9 to 1.8, and 3.1 to 4.3, respectively.

Table 3.3. Intra-class correlation coefficients (ICC) (95% confidence interval (CI)), measurement bias/ratio (log-transformed data) */÷ 95% ratio limits of agreement (rLOA) and typical error of measurement as coefficient of variation (CV) (95% confidence limits) of physiological variables and time-to-exhaustion

	ICC (95% confidence interval)	Measurement bias/ratio (*/÷ 95% rLOA)	CV (%) (95% confidence limits)
VO_2 (L. min^{-1})			
First stage	0.90 (0.73-0.97) ‡	1.03 */÷ 1.08	2.9 (2.2-4.3)
Second stage	0.91 (0.74-0.97) ‡	1.02 */÷ 1.09	3.1 (2.4-4.6)
Third stage	0.95 (0.84-0.98) ‡	1.02 */÷ 1.07	2.4 (1.8-3.6)
VO_2 (mL.kg^{-1}.min^{-1})			
First stage	0.93 (0.79-0.98) ‡	1.02 */÷ 1.07	2.3 (1.8-3.5)
Second stage	0.93 (0.80-0.98) ‡	1.01 */÷ 1.08	2.9 (2.2-4.3)
Third stage	0.96 (0.89-0.99) ‡	1.01 */÷ 1.06	2.2 (1.7-3.3)
C_R (mL.$kg^{-0.75}$.m^{-1})			
First stage	0.92 (0.77-0.97) ‡	1.01 */÷ 1.07	2.5 (1.9-3.7)
Second stage	0.90 (0.75-0.97) ‡	1.01 */÷ 1.08	2.9 (2.2-4.4)
Third stage	0.91 (0.75-0.97) ‡	1.01 */÷ 1.06	2.2 (1.7-3.3)
V_E (mL.min^{-1})			
First stage	0.73 (0.32 to 0.90) †	1.02 */÷ 1.16	5.3 (4.0-7.8)
Second stage	0.82 (0.52 to 0.94) ‡	1.03*/÷ 1.15	5.0 (3.8-7.4)
Third stage	0.86 (0.57 to 0.95) ‡	1.00 */÷ 1.14	4.8 (3.7-7.2)
VCO_2 (L.min^{-1})			
First stage	0.78 (0.45-0.92) ‡	1.01 */÷ 1.14	4.9 (3.7-7.4)
Second stage	0.64 (0.18-0.87) ‡	1.01 */÷ 1.24	7.9 (6.0-12)
Third stage	0.76 (0.39-0.91) ‡	1.01 */÷ 1.23	7.7 (5.8-11.6)
RER			
First stage	0.08 (-0.57 to 0.46)	0.98 */÷ 1.12	4.2 (3.2-6.3)
Second stage	0.35 (-0.43 to 0.59)	0.99 */÷ 1.14	4.7 (3.6-7.0)
Third stage	0.17(-0.50 to 0.53)	0.98 */÷ 1.18	6.1 (4.6-9.0)
HR (b.min^{-1})			
First stage	0.84 (0.58 to 0.95) ‡	1.01 */÷ 1.03	2.9 (2.2-4.3)
Second stage	0.92 (0.78 to 0.97) ‡	1.00 */÷ 1.02	1.6 (1.2-2.4)
Third stage	0.96 (0.87 to 0.99) ‡	1.00 */÷ 1.02	1.0 (0.8-1.5)
RPE			
First stage	0.82 (0.59-0.93) ‡	1.06 */÷ 1.09	3.4 (2.6-5.0)
Second stage	0.85 (0.59-0.95) ‡	0.98 */÷ 1.06	4.3 (3.3-6.5)
Third stage	0.89 (0.66-0.94) ‡	1.00 */÷ 1.06	3.1 (2.3-4.6)
TTE (s)			
Third stage	0.94 (0.81-0.98) ‡	0.99 */÷ 1.18	9.2 (4.7-15.6)

VO_2 = oxygen uptake, C_R = cost of running, V_E = ventilation, VCO_2 = carbon dioxide production RER = respiratory exchange ratio, HR = heart rate, RPE = rating of perceived exertion, TTE = time-to-exhaustion

†$P<0.01$, ‡$P<0.001$

3.4 Discussion

The major findings in the current study are that TTE and RPE were reliable when conducted as part of a RE test. In addition, various physiological variables were reliable at different intensities of VT_2 whereas the reliability for VCO_2 and RER were questionable amongst a heterogeneous cohort. As expected, the VO_{2max} and running speed was significantly greater for the TR than METM which provides a heterogeneous sample when pooled for reliability analyses.

According to the results, RPE showed moderate reliability across the three stages (ICC = 0.82-0.89) and CV varying from 3.1-4.3%. Whilst there are no previous reports indicating the reliability of RPE for RE tests combined with TTE to the authors' knowledge, Doherty et al (2001) did examine the reliability of perceived exertion using Borg's RPE scale during treadmill running to exhaustion and showed a moderate reliability (ICC = ∼0.82) at four different time points. Moreover, Doherty et al (2001) reported that the possible difference in RPE between the two trials should lie within ~0 ± 2 according to the LOA (95%). Accordingly, the rLOA for RPE from the current study was approximately 1.01 */÷ 1.07 for the three stages, indicating that an RPE of 20 or below would fall within the range of ± 2, which agrees with that reported by Doherty et al (2001).

The TTE across RE trials 1 and 2 showed high reliability (ICC = 0.94) with a mean difference of 13 seconds. These results demonstrate higher reliability than previous reports for running TTE at intensities equivalent to 1500 m and 5 km distances (ICC = 0.46 and 0.57, respectively) (Laursen, et al., 2007) and with running TTE at 95% and 90% of VO_{2max} (ICC = 0.80 and 0.75, respectively) (Midgley, McNaughton, & Carroll, 2007). Time-to-exhaustion did indicate greater within-participant variability (CV = 9.2%) across RE trials 1 and 2 compared to the other variables that have demonstrated equal reliability (i.e. VO_2 and HR). However, the variability for TTE in the current study is smaller than reports given by Billat et al (CV = 25%) (1994) and Harling et al (CV = 15%) (2003) with running TTE at VO_{2max} and by Hickson et al (2005) with running speeds adjusted to elicit exhaustion with durations of approximately 2-, 4- and 8 minutes (CV = 9.2, 13 and 16%, respectively). Whilst TTE in the current study showed high reliability which appears to be more acceptable than that of previous reports, the rLOA indicated questionable agreements (95% rLOA = 0.99 */÷ 1.18). The high reliability in contrast to a questionable agreement may be a result of sample heterogeneity (Atkinson & Nevill, 1998). Nonetheless, the authors confirm that the incorporation of TTE in a RE test may be useful as indicated by the within-participant variability (CV = 9.2%) being less than that of previous literature (Billat, et al., 1994; Harling, et al., 2003; Hickson & Hopkins, 2005). In addition, whilst the aerobic demand of RE as an indication of running performance is well established, TTE provides a more practical measurement of monitoring athletes' training or assessing whether running performance is affected by an intervention.

The C_R, absolute VO_2 and relative VO_2 showed no significant differences between RE trial 1 and 2 for the three stages with low percentages of CV which confirms previous studies (Morgan, et al., 1994; Pereira & Freedson, 1997; Saunders, et al., 2004a). The rLOA for C_R, absolute VO_2 and relative VO_2 (*/÷ 95% ratio) ranged from 1.06 to 1.09, indicating that the difference in energy cost between the two RE trials due to measurement– and biological error will typically be neither more nor less than 6-9%. This demonstrates a narrow rLOA and small within-participant variability across the two RE trials for the three stages.

Directly comparing the intra-individual variability from the current study with literature is at present difficult, as studies have not yet assessed the agreement between measurements of the aerobic demand of RE according to the technique by Bland et al (1986). However, the results from the current study are similar to that reported for outrigger canoeing (rLOA = 1.08-1.09) (Sealey, et al., 2010) and smaller than that for arm crank ergometry (rLOA = 1.11-1.12) (Leicht & Spinks, 2007). Sealey et al (2010) and Leicht et al (2007) reported VO_2 as peak values which are not indicative of C_R. Nevertheless, the agreement ratios of the RE test for the current study were close to 1.06, which is regarded as excellent (Neville & Atkinson, 1997).

The absolute VO_2, relative VO_2 and C_R indicated high reliability (ICC = 0.90-0.97) for RE across the two trials and confirms the results by Morgan et al (1994) for the aerobic demand of RE (ICC = 0.95). Whilst the protocols used in the current study and that by Morgan and authors (1994) are different, with Morgan and colleagues (1994) conducting a continuous running protocol and incorporating a homogenous group of trained distance runners, the similarities in the aerobic demand from the two RE trials demonstrates that the RE test in the current study is reliable amongst a heterogeneous cohort at various speeds. Moreover, the greater reliability and lesser intra-individual variability for C_R and relative VO_2 compared to absolute VO_2 demonstrates that the stability of the protocol is greater by expressing the aerobic demand in relative terms.

In contrast to the C_R in the current study, V_E and RER showed a larger variation ranging from 4.8-5.3% and 4.2-6.1%, respectively. However, the CV for HR ranged from 1.0-2.9% showing smaller variability than the C_R. These results are similar to Saunders and colleagues (2004b) who measured CV between two RE trials for V_E (6.6-8.3%), HR (1.7-2.4%) and RER (3.4-4.4%) at varying speeds. Pereira and colleagues (1997) showed no significant differences for V_E, HR and RER between two RE trials at a continuous speed, however, the variability was not measured. In the current study, the reliability was moderate to high for HR (ICC = 0.84-0.96, rLOA = 1.02-1.03) and questionable for RER (ICC = 0.08-0.35, rLOA = 1.14-1.16) and VCO_2 (ICC = 0.64-0.78, rLOA = 1.14-1.24) for each of the three stages and moderate for V_E (ICC = 0.82-0.86, rLOA = 1.12-1.18) during the last two stages. The low ICC values for RER may be attributed to the questionable reliability of VCO_2, which is similar to findings by Leicht et al (2007) during arm crank ergometry. Whilst the usability of VCO_2 appears to be of concern, the incorporation of RER may still be an effective means of assessing running performance across trials as the intra-individual variability was similar to V_E and TTE which had greater reliability. However, further assessment on the variability of RER across a greater number of RE trials is warranted.

Whilst the investigation of the repeatability of RE amongst a heterogeneous cohort is limited, Pereira et al (2007) reported small intra-individual variability separately for highly trained and moderately trained males (CV = 1.77% and 2.00%, respectively) across two RE trials. Morgan and colleagues (1994) also showed similar intra-individual variability in sub-maximal running for male and female distance runners (CV = ~1.76% and 1.78%, respectively) despite differences of ~10 $mL.kg^{-1}.min^{-1}$ in VO_{2max} between genders. Such findings indicate that fitness level or training backgrounds may have minimal impact on the intra-individual variability of RE across trials.

Whilst the intra-individual variability was minimal in the current study, the inter-individual variability would be of concern amongst trained and moderately trained participants and subsequently affect the power of statistical analyses. As demonstrated, the inter-individual variability for absolute VO_2 ($L.min^{-1}$) and relative VO_2 ($mL.kg^{-1}.min^{-1}$) between RE trials 1 and 2 was ~10-11%. However, when the C_R was expressed as VO_2 $mL.kg^{-0.75}.m^{-1}$, the inter-individual variability was reduced to ~8%, which is less than the studies that incorporated homogenous samples and reported the aerobic demand for RE expressed relative to body mass ($mL.kg^{-1}.min^{-1}$) (Pereira & Freedson, 1997; Billat et al., 1994). Although Helgerud and colleagues (2001; 2010) have shown inter-individual variation of ≤ 5%, the current study demonstrates that inter-individual variability can be minimized when the aerobic demand for RE is expressed as C_R (VO_2 $mL.kg^{-0.75}.m^{-1)}$ rather than absolute or relative VO_2 ($mL.min^{-1}$ or $mL.kg^{-1}.min^{-1}$, respectively). Subsequently, it is recommended to express aerobic demand of RE relative to body mass raised to the power of 0.75 and meter in order to control for inter-individual variability.

3.5 Conclusion

In conclusion, numerous physiological and performance variables are reliable during RE at various running speeds amongst a heterogeneous cohort. This suggests that small changes in the physiological variables within the current protocol may be sufficient to indicate attenuation of running performance as a result of a particular intervention.

Chapter 4

The reliability of lower extremity and thoracic kinematics at various running speeds

Doma, K., Deakin, G.B., & Sealey, R.M. (2012). The reliability of lower extremity and thoracic kinematics at various running speeds. *International Journal of Sports Medicine*, *33*(5), 364-369.

4.1 Introduction

Running economy refers to the oxygen cost of running at a given running speed (Saunders, Pyne, Telford, & Hawley, 2004). Whilst physiological parameters have predominantly been used to indicate RE, researchers have recently investigated three-dimensional (3-D) kinematics as an indication of running performance. Studies have examined running gait parameters following down-hill running (Chen et al., 2007), resistance training (Snyder, Earl, O'Connor, & Ebersole, 2009), sprint training (Alcaraz, Palao, Elvira, & Linthorne, 2008) and stretching (Caplan, Rogers, Parr, & Hayes, 2009). The exercise training interventions caused significant changes to lower extremity joint kinematics during sub-maximal running protocols, demonstrating the importance of analysing running gait pattern as an indication of running performance. However, factors including retro-reflective marker reapplication errors, girth measurement errors and the inherent changes in human locomotion can augment between-day variability. Subsequently, it is important to measure the repeatability of the running gait parameters to identify whether gait pattern is perturbed by the experimental intervention.

Studies examining the repeatability of running gait parameters in 3-D have documented high reliability for hip, knee and ankle joint kinematics in the sagittal plane with low reliability in the transverse– and frontal planes (Diss, 2001; Ferber, McClay Davis, Williams, & Laughton, 2002). However, these studies examined the kinematics of overground running which has been reported to induce greater variability in locomotion than treadmill gait due to participants aiming their foot on the force plate, rendering an unnatural gait pattern (Dingwell, Cusumano, Cavanagh, & Sternad, 2001). Pohl et al. (2010) and Noehren et al. (2010) have examined the repeatability of running gait pattern on a treadmill and showed a high reliability in joint kinematics for the hip and knee joints in frontal and transverse planes. Pohl and authors (2010) suggested that between-session variability in joint kinematics may be minimized on a treadmill due to the constant running speed and reduced side-to-side motion.

Whilst Pohl et al. (2010) and Noehren et al. (2010) demonstrated high reliability in 3-D running gait kinematics, the duration of the running protocol was set for two to three minutes which is not applicable to a common RE protocol where running is performed for a minimum of 5 minutes at a constant sub-maximal intensity to ensure that steady-state has been reached (Saunders, et al., 2004a). Moreover, the running gait analyses have been limited to lower extremity joints and little is known regarding the reliability of kinematics of the thorax during RE. Studies have also shown that the oxygen cost of running is reliable at various running speeds for RE (Billat, et al., 1994; Ferber, et al., 2002; Pohl, et al., 2010) however, such investigation for the kinematics of running gait has not been conducted as far as the authors are aware. In addition, the majority of the studies that have examined the reliability of running gait parameters have incorporated homogenous samples which are often limited in accessibility and the practicality of such findings can only be applied to that specific cohort. Heterogeneous samples would enhance participant recruitment and the kinematic findings would apply to a wider demographic.

The current study tested the hypothesis that the reliability of the lower extremity and the thorax in the sagittal plane would be higher than the reliability of the kinematic parameters in the frontal– and transverse plane at various running speeds amongst a heterogeneous cohort. Determining the reliability of the kinematics in the lower extremity and thorax at various running speeds will demonstrate the usability of running gait analyses during widely used and accepted RE protocols.

4.2 Methods

Participants

Seven METM and 7 male TR participated in the study (**Table 4.1**). The METM were running 5-10 km per week of which the majority of the distances were covered in various sports (e.g. soccer, basketball and cricket). The TR were middle to long distance (1,500-10,000 m) runners who covered at least 50 $km.week^{-1}$ and had all ran a 10,000 m time trial within 37 minutes during the last 6 months. Each participant completed informed consent prior to participating in any testing procedures. All procedures in this study were approved by the

Institutional Human Research Ethics Committee and were conducted in accordance with the ethical standards of the International Journal of Sports Medicine (Harriss & Atkinson, 2011).

Table 4.1. The mean ± standard deviation of the physical characteristics of the trained runners and moderately endurance trained participants

Variables	Participants (n = 14)
Age (years)	22.85 ± 4.97
Height (m)	1.81 ± 0.07
Mass (kg)	73.61 ± 7.67
VO_{2max} ($mL.kg^{-1}.min^{-1}$)	64.01 ± 6.28
70% VT_2 ($km.h^{-1}$)	10.11 ± 1.86
90% VT_2 ($km.h^{-1}$)	13.43 ± 1.84
110% VT_2 ($km.h^{-1}$)	16.57 ± 5.92
%VO_{2max} @ VT_2	88 ± 4

VO_{2max} = maximal oxygen consumption; VT_2 = second ventilatory threshold; %VO_{2max} @ VT_2 = percentage maximal oxygen consumption at the second ventilatory threshold

Research design

Following a familiarisation session, participants completed a VO_{2max} test using a portable Cosmed $K4b^2$ gas analyser (Cosmed, Italy, Rome) on a treadmill (Quinton Q65, USA) to determine the VT_2, which was used to determine the running speed for the RE test. The VT_2 was determined by identifying the inflection point of V_E with respect to VCO_2 on a scatter diagram (Noehren, et al., 2010). Two days following the VO_{2max} test, participants completed two identical RE tests to analyse running kinematics, with these tests separated by 2-5 days in order to limit bias from insufficient recovery (Atkinson, & Neville, 1998). The VO_{2max} test was a continuous incremental run to exhaustion commencing at 12 $km.h^{-1}$ with the speed increasing by 1.5 $km.h^{-1}$ every minute at 0% gradient.

Running economy test

The RE protocol was a three stage discontinuous incremental test. The participants ran for 10 minutes during the first two stages with a 2 minute passive recovery period between each stage. The running speed was set at 70–, 90– and 110% of VT_2 for the three stages, respectively, with the last stage set to exhaustion. For each motion capture, at least 10 strides of kinematic data were recorded at 100 Hz using a 3-D 8-camera optical motion analysis system (VICON Motion Systems, Oxford, UK). The optical cameras were statically calibrated for each testing session and ensured an image error of < 0.15 pixels. The measuring volume covered 1.5 m x 3 m x 2 m (width, length, height). The segmented model consisted of the thorax, pelvis, thighs, shank and the feet using 21 retro-reflective markers (14 mm diameter) that were placed by a single well trained investigator in accordance with Nexus Plug-in Gait Model (VICON®, 2008). Running gait parameters included ankle range of motion (A_{ROM}), maximum knee flexion during swing (KF_S), maximum knee flexion after foot strike (KF_{AS}) and hip range of motion (H_{ROM}) in the sagittal plane; hip abduction/adduction ($H_{AB/AD}$), lateral flexion of the pelvis (PLV_{LF}) and lateral flexion of the thorax (THX_{LF}) in the frontal plane; and hip internal/external rotation ($H_{IN/IEX}$), pelvic rotation (PLV_R) and thoracic rotation (THX_R) in the transverse plane. Raw kinematic data were filtered using Woltring filtering routine. The mean-squared error (MSE) was set to 20 mm^2 in accordance with a detailed residual analysis (Winter, 2008). Running gait was captured at 9 minutes 30 seconds during the first two stages and every 30 seconds during the last stage. The kinematic data collected at mid-point during the last stage was used for analysis (e.g. the 6th motion capture was analysed when 11 motion captures were obtained). When an even number of motion capture was obtained during the last stage, the latter half of the kinematic data was analysed (e.g. the 7^{th} motion capture was analysed when 12 motion captures were obtained).

Statistical analyses

The data are expressed as mean ± inter-individual standard deviation. All data were analysed using the Statistical Package for Social Sciences (SPSS, version 18, Chicago, IL). The test-retest reliability of the running gait parameters was assessed using the ICC (SPSS two-way mixed, 95% CI) and 95% rLOA (Bland, & Altman, 1986). According to Vincent (2005), ICC values above 0.9, between 0.80 to 0.89 and below 0.80 were considered high, moderate and questionable, respectively. Within-participant CV with associated 95% CI was reported for the kinematic measures. Normality assumptions were violated using histograms, normal probability plots and Shapiro-Wilk's test. Subsequently, the Wilcoxon Signed Rank test was used in order to determine differences in the running gait parameters between the two RE trials. Whilst the data was homoscedastic (an example of a Bland and Altman Plot of H_{ROM} during the first stage as depicted in **Figure 4.1**) the results were transformed using natural logarithms before calculating rLOA as normality assumptions were violated (Neville, & Atkinson, 1997). The worthwhile changes in angular displacement of the running gait parameters were determined based on a nomogram for the estimation of the measurement repeatability error in accordance with the ratio rLOA (Atkinson & Nevill, 2006). Worthwhile changes for the current sample size (n = 14) as well as hypothetical sample sizes of 30 and 40 were calculated using the following linear regression equations:

$$y = 41.58x-41.48 \quad (1)$$

$$y = 30.50x - 30.39 \quad (2)$$

$$y = 26.40x - 26.40 \quad (3)$$

Whilst it has been suggested that studies should incorporate at least 40 participants for limiting error statistics (Atkinson, & Neville, 2006), worthwhile changes for sample sizes of 14 and 30 have also been quantified in order to provide a degree of measure of what would be required with a sample size that is commonly used to detect kinematic differences between treatments. Neville and Atkinson (1997) also suggested that an agreement ratio of */÷ 1.06 (i.e. 95% of ratios within 6% of the mean bias ratio) is regarded as excellent whereas */÷ 1.29 is unacceptable. Subsequently, delimitations will be decided by determining the agreement ratio and its proximity to */÷ 1.06 in conjunction with ICC. In summary, scores required to achieve high/excellent reliability for the current paper has been set at: ICC $\geq$ 0.9 and rLOA $\leq$ 1.06 (Neville, & Atkinson, 1997; Vincent, 2005). Statistical significance was established at the 0.05 level. Instead of differentiating the findings between METM and TR, the results are reported as a pooled data in order to achieve the aim of assessing the reliability of running kinematics amongst a heterogeneous sample.

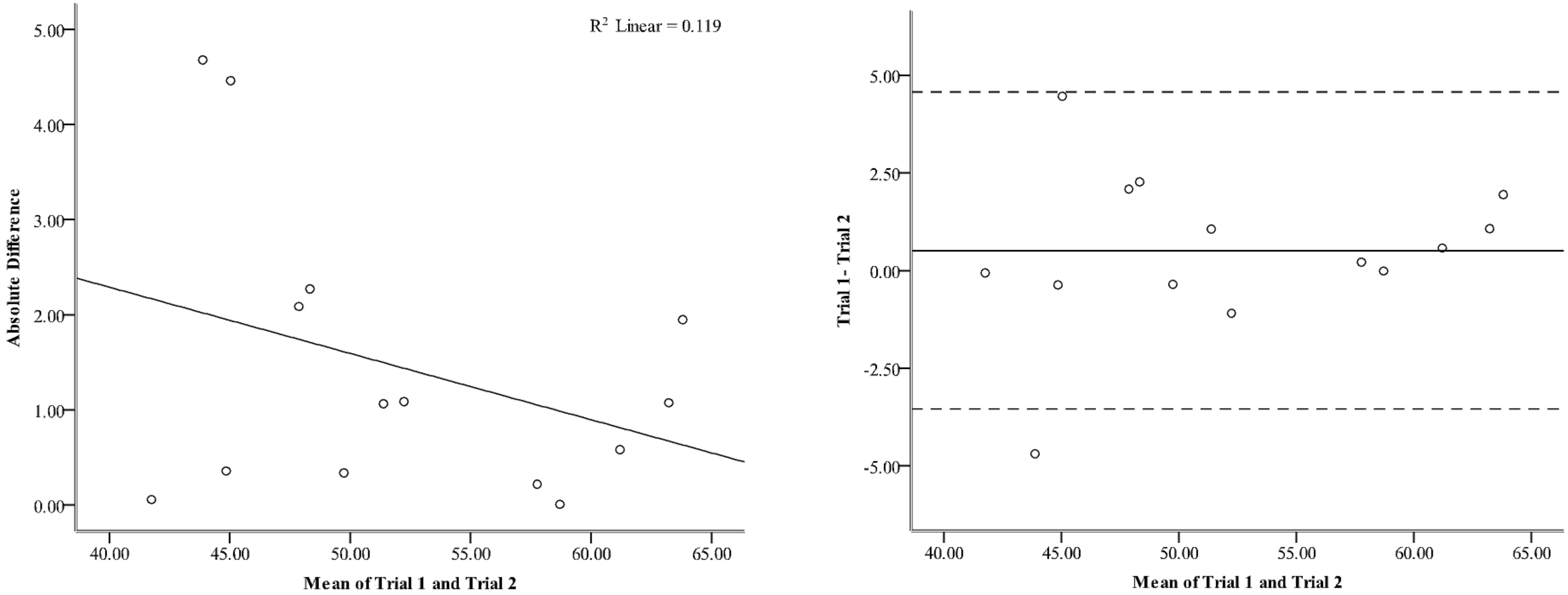

Figure 4.1. Bland and Altman Plot of the absolute difference between trials 1 and 2 against the mean of trials 1 and 2 (left graph) and the difference between trials 1 and 2 against the mean of trials 1 and 2 (right graph) of the hip range of motion during the first stage. The centre line of the bottom graph indicates the mean difference between trials 1 and 2 and the upper and lower dashed lines indicates mean difference ± 1.96 times the standard deviation of the difference

4.3 Results

There were no significant differences ($P \geq 0.05$) in the majority of the angular displacements of the selected running gait parameters during the three stages across two RE trials (**Table 4.2**). However, the angular displacement of KF_S for RE trial 1 was significantly greater than RE trial 2 during the last stage ($P < 0.05$).

The ICC, rLOA and CV for A_{ROM}, KF_S, KF_{AS}, H_{ROM}, $H_{IN/IEX}$, $H_{AB/AD}$, PLV_R, THX_R, PLV_{LF}, and THX_{LF} ranged from 0.33-0.96, 1.03-1.39 and 2.0-18.6%, respectively (**Table 4.3**). The worthwhile changes for sample sizes 14, 30 and 40 ranged from 1.3-16.3%, 1.0-12.0% 0.8-10.3%, respectively (**Table 4.4**).

Table 4.2. The mean ± standard deviation of the angular displacement of the running gait parameters in degrees (°) averaged for ten strides during the three stages of the running economy (RE) trials

	RE trial 1	RE trial 2	Δ between trials
Sagittal plane			
A_{ROM}			
Stage 1	48.95 ± 5.43	48.79 ± 5.51	0.16
Stage 2	51.84 ± 5.82	53.10 ± 5.54	-1.26
Stage 3	53.60 ± 5.41	55.60 ± 6.37	-2.00
KF_S			
Stage 1	91.14 ± 14.43	90.57 ± 13.79	0.57
Stage 2	107.48 ± 14.01	106.69 ± 14.11	0.79
Stage 3	120.03 ± 15.57	116.29 ± 14.71*	3.74
KF_{AS}			
Stage 1	38.35 ± 6.36	38.40 ± 6.18	-0.05
Stage 2	40.73 ± 5.99	40.78 ± 6.20	-0.05
Stage 3	41.53 ± 6.58	41.12 ± 6.87	0.41
H_{ROM}			
Stage 1	52.37 ± 7.76	51.86 ± 7.41	0.51
Stage 2	62.88 ± 9.50	62.12 ± 9.67	0.76
Stage 3	73.21 ± 8.66	71.92 ± 8.96	1.29
Frontal plane			
$H_{AB/AD}$			
Stage 1	27.10 ± 7.67	23.65 ± 8.75	3.45
Stage 2	30.10 ± 10.90	26.89 ± 8.96	3.21
Stage 3	33.15 ± 11.73	29.82 ± 11.05	3.33
PLV_{LF}			
Stage 1	13.73 ± 3.03	14.14 ± 3.45	-0.41
Stage 2	16.27 ± 3.83	16.45 ± 2.56	-0.18
Stage 3	19.96 ± 3.13	20.12 ± 2.95	-0.16
THX_{LF}			
Stage 1	25.85 ± 4.66	26.30 ± 5.05	-0.45
Stage 2	30.67 ± 5.34	30.84 ± 5.60	-0.17
Stage 3	36.56 ± 6.12	34.67 ± 6.87	1.89
Transverse plane			
$H_{IN/IEX}$			
Stage 1	15.63 ± 4.69	16.01 ± 4.52	-0.38
Stage 2	18.14 ± 5.12	18.81 ± 5.06	-0.67
Stage 3	21.76 ± 4.65	21.67 ± 4.85	0.09
PLV_R			
Stage 1	6.31 ± 3.27	6.46 ± 2.74	-0.15
Stage 2	9.05 ± 4.42	9.05 ± 3.71	0
Stage 3	11.54 ± 5.14	10.89 ± 4.71	0.65
THX_R			
Stage 1	6.86 ± 1.99	6.72 ± 1.84	0.14
Stage 2	8.04 ± 2.30	7.88 ± 2.45	0.16
Stage 3	9.99 ± 3.84	9.64 ± 3.63	0.35

A_{ROM} = ankle range of motion ; KF_S = maximum knee flexion during swing; KF_{AS} = maximum knee flexion after foot strike; H_{ROM} = hip range of motion; $H_{AB/AD}$ = hip abduction/adduction; PLV_{LF} = lateral flexion of pelvis; THX_{LF} = lateral flexion of thorax; $H_{IN/IEX}$ = hip internal/external rotation; PLV_R = pelvic rotation; THX_R = thoracic rotation

*$P < 0.05$ values significantly different from RE trial 1

Table 4.3. Intra-class correlation coefficients (ICC) at 95% confidence interval (CI), measurement bias/ratio (log-transformed data) (*/÷ 95% ratio limits of agreement (rLOA)) and within-participant coefficient of variation at 95% CI of the running gait parameters between two RE trials

	ICC (95% CI)	Measurement bias/ratio (*/÷ 95% ratio rLOA)	CV (95% CI)
Sagittal plane			
A_{ROM}			
Stage 1	0.80 (0.49-0.93)**	1.00 */÷ 1.06	4.1 (2.7-5.6)
Stage 2	0.84 (0.56-0.94)**	0.99 */÷ 1.05	3.5 (1.5-5.2)
Stage 3	0.70 (0.29-0.89)**	0.98 */÷1.07	3.9 (0.8-7.3)
KF_S			
Stage 1	0.97 (0.90-0.99)**	1.00 */÷ 1.04	2.2 (1.3-3.2)
Stage 2	0.97 (0.90-0.99)**	1.00 */÷ 1.03	2.4 (0.5-4.4)
Stage 3	0.96 (0.89-0.99)**	1.01 */÷ 1.03	2.8 (0.6-5.5)
KF_{AS}			
Stage 1	0.85 (0.60-0.95)**	1.00 */÷ 1.08	5.2 (3.3-7.1)
Stage 2	0.84 (0.57-0.95)**	1.00 */÷ 1.08	4.3 (1.9-7.0)
Stage 3	0.76 (0.84-0.98)**	0.99 */÷ 1.09	6.0 (3.3-9.5)
H_{ROM}			
Stage 1	0.96 (0.89-0.99)**	1.00 */÷ 1.04	2.0 (0.8-3.2)
Stage 2	0.96 (0.88-0.99)**	1.01 */÷ 1.04	2.3 (1.0-3.6)
Stage 3	0.94 (0.83-0.98)**	1.01 */÷ 1.04	2.6 (1.5-3.8)
Frontal plane			
$H_{AB/AD}$			
Stage 1	0.63 (0.17-0.86) **	1.08 */÷ 1.30	17.8 (10.8-24.8)
Stage 2	0.40 (-0.15-0.76)	1.05 */÷ 1.34	18.6 (5.9-32.0)
Stage 3	0.33 (-0.23-0.72)	1.05 */÷ 1.39	18.4 (3.1-33.3)
PLV_{LF}			
Stage 1	0.92 (0.77-0.97)**	0.99 */÷ 1.10	5.6 (3.3-7.8)
Stage 2	0.78 (0.45-0.92)	0.99 */÷ 1.12	6.7 (3.6-7.9)
Stage 3	0.75 (0.38-0.91)	1.00 */÷ 1.11	5.7 (2.5-8.9)
THX_{LF}			
Stage 1	0.80 (0.45-0.93)**	0.99 */÷1.11	5.8 (2.1-9.5)
Stage 2	0.82 (0.54-0.94)**	1.00 */÷ 1.09	5.9 (3.0-8.3)
Stage 3	0.91 (0.74-0.97) **	1.02 */÷ 1.07	5.3 (2.6-8.4)
Transverse plane			
$H_{IN/IEX}$			
Stage 1	0.82 (0.53-0.94)	0.99 */÷ 1.16	8.8 (3.9-13.8)
Stage 2	0.81 (0.51-0.94)	0.98 */÷ 1.14	9.3 (5.0-14.4)
Stage 3	0.73 (0.34-0.90)	1.00 */÷ 1.14	9.0 (4.4-12.3)
PLV_R			
Stage 1	0.79 (0.47-0.93)**	0.98 */÷ 1.35	16.3 (8.5-24.1)
Stage 2	0.77 (0.40-0.92)**	0.99 */÷ 1.38	16.6 (8.4-24.5)
Stage 3	0.83 (0.52-0.94)**	1.03 */÷ 1.33	14.3 (8.2-21.3)
THX_R			
Stage 1	0.96 (0.88-0.99)**	1.00 */÷ 1.09	3.9 (1.5-6.3)
Stage 2	0.88 (0.67-0.96)**	0.92 */÷ 1.14	7.9 (3.5-10.9)
Stage 3	0.97 (0.91-0.99)**	1.01 */÷ 1.07	5.3 (2.6-8.4)

A_{ROM} = ankle range of motion ; KF_S = maximum knee flexion during swing; KF_{AS} = maximum knee flexion after foot strike; H_{ROM} = hip range of motion; $H_{AB/AD}$ = hip abduction/adduction; PLV_{LF} = lateral flexion of pelvis; THX_{LF} = lateral flexion of thorax; $H_{IN/IEX}$ = hip internal/external rotation; PLV_R = pelvic rotation; THX_R = thoracic rotation

* $P < 0.05$; ** $P < 0.01$

Table 4.4. Percentage of the worthwhile differences (WD) for the current sample size (n = 14), hypothetical sizes of 30 (Sample 30) and 40 (Sample 40) calculated in accordance with the ratio limits of agreement of the running gait parameters between two RE trials

	Current sample WD (%)	Sample 30 WD (%)	Sample 40 WD (%)
Sagittal plane			
A_{ROM}			
Stage 1	2.6	1.9	1.6
Stage 2	2.2	1.9	1.6
Stage 3	3.0	2.3	1.9
KF_S			
Stage 1	1.8	1.3	1.0
Stage 2	1.3	1.0	0.8
Stage 3	1.3	1.0	0.8
KF_{AS}			
Stage 1	3.4	2.6	2.1
Stage 2	3.4	2.6	2.1
Stage 3	3.8	2.9	2.4
H_{ROM}			
Stage 1	1.8	1.3	1.1
Stage 2	1.8	1.3	1.1
Stage 3	1.8	1.3	1.1
Frontal plane			
$H_{AB/AD}$			
Stage 1	12.6	9.3	7.9
Stage 2	14.2	10.5	8.0
Stage 3	16.3	12.0	10.3
PLV_{LF}			
Stage 1	4.3	3.2	2.6
Stage 2	5.1	3.8	3.2
Stage 3	4.7	3.5	2.9
THX_{LF}			
Stage 1	4.7	3.5	2.9
Stage 2	3.8	2.9	2.4
Stage 3	3.0	2.3	1.9
Transverse plane			
$H_{IN/IEX}$			
Stage 1	6.7	5.0	4.2
Stage 2	5.9	4.4	3.7
Stage 3	5.9	4.4	3.7
PLV_R			
Stage 1	14.6	10.8	9.2
Stage 2	15.9	11.7	10.0
Stage 3	13.8	10.2	8.7
THX_R			
Stage 1	3.8	2.9	2.4
Stage 2	5.9	4.4	3.7
Stage 3	3.0	2.3	1.9

A_{ROM} = ankle range of motion ; KF_S = maximum knee flexion during swing; KF_{AS} = maximum knee flexion after foot strike; H_{ROM} = hip range of motion; $H_{AB/AD}$ = hip abduction/adduction; PLV_{LF} = lateral flexion of pelvis; THX_{LF} = lateral flexion of thorax; $H_{IN/IEX}$ = hip internal/external rotation; PLV_R = pelvic rotation; THX_R = thoracic rotation

4.4 Discussion

The present study was an examination of the reliability of lower extremity and thoracic running gait parameters at various running speeds. The findings demonstrated that the majority of the running kinematics were reliable at various running speeds amongst a heterogenous cohort. Specifically, the reliability of joint kinematics in the sagittal plane was greater than the reliability of joint kinematics in the transverse– and frontal planes, accepting the hypothesis.

The WD for A_{ROM}, KF_S, KF_{AS} and H_{ROM} ranged from 2.6-3.0%, 1.3-1.8%, 3.4-3.8% and 1.8%, respectively, during the three stages in accordance with the sample size of the current study. These values indicate that the kinematic variables in the sagittal plane are statistically sensitive to changes as they are substantially lower than previous studies that have reported percentage mean differences of hip (47%), knee (16%) and ankle (21%) angular displacements with significant differences as a result of exhaustive interventions amongst trained and moderately trained runners (Diss, 2001; Dutto & Braun, 2004; Kellis & Liassou, 2009; Pohl, et al., 2010). Additionally, the CV for these variables was on average 2.6% which is within the range of 1.5-5% of the intra-individual variability of the oxygen cost of running reported by well controlled studies (Saunders, et al., 2004b). However, the CV of the hip, pelvis and thorax in the transverse and frontal planes were relatively higher with an average of 10.1%. This may be due to differences in the complexity of the movements executed at various degrees of freedom. The angular displacements in the sagittal plane act as primary movements to propel the body centre of gravity forward during running which is a more simplified task than movements executed in the transverse and frontal planes which functions to stabilize the body. In addition, given that the power is transferred from the lower to the upper extremity in sequence through the kinetic chain, between-session variability may be augmented with each stride in the upper body.

The H_{ROM} and KF_S for the 3 stages showed a high reliability (ICC>0.90) demonstrating that the alteration in running speed does not impact the repeatability of these running gait parameters and confirms previous studies that have investigated the repeatability of hip and knee kinematics at single running speeds (Diss, 2001; Ferber, et al., 2002; Morgan, Daniels, Carlson, Filarski, & Landle, 1991; Noehren, et al., 2010; Pohl, et al., 2010). The KF_{AS} showed a moderate reliability across trials which indicated less reliability compared to peak knee flexion during the swing phase (KF_S). Such findings may be attributed to differences in the contribution of muscle groups in the lower extremity at various stages of running gait. For example, the knee extensor muscles undergo eccentric– to concentric contractions at KF_{AS} to convert their musculoskeletal functions from absorbing impact to elevating the body off the ground via knee extension. This transfer between gait cycle events necessitates the use of complex morphological and mechanical properties of the lower extremity to stabilize the body which may induce between-session variances in joint kinematics. In comparison, KF_S may have shown greater reliability as peak joint angle was obtained during this particular kinematic event and that the lower extremity was driven forward by momentum during the swing phase which may have contributed to stabilizing the joint. Similar to the reliability of KF_{AS}, the A_{ROM} showed a moderate reliability between the two RE trials and agrees with results from previous reports (Ferber et al., 2002; Noehren et al., 2010). As running technique can alter between mid-foot- to heel-strike, the moderate reliability of A_{ROM} may be due to participants initiating slight adjustments in the position of the foot at the point of contact with the ground.

The rLOA for A_{ROM} and KF_{AS} ranged from 1.05-1.07 and 1.08-1.09, respectively, for the three stages which appear larger than the 2.5-6.8° range of ankle plantar– and dorsi-flexion and knee flexion variability shown previously by Wolf et al (2009). However, because these authors (Wolf et al., 2009) reported levels of agreement as absolute values compared to the current results as relative values it is difficult to directly compare the findings by Wolf et al (2009) and the current study. Nonetheless, the rLOA for A_{ROM} and KF_{AS} were close to 1.06 which has been regarded as excellent (Neville, & Atkinson, 1997) and the CV were relatively low (CV = 3.5-6.0%) demonstrating the effectiveness of using these kinematic variables as measures of running performance.

The THX_R and THX_{LF} showed moderate to high reliability signifying the potential of incorporating the kinematics of the thorax in the transverse– and frontal planes for running gait analyses. However, $H_{AB/AD}$, PLV_R and PLV_{LF} indicated questionable reliability (ICC<0.8) and confirm previous studies that have examined the reliability of lower extremity joint kinematics for running (Ferber et al., 2002) and walking (Maynard, Bakheit, Oldham, & Freeman, 2003; Miana, Prudencio, & Barros, 2009). Additionally, $H_{AB/AD}$ and PLV_R demonstrated substantially higher within-participant variability (CV = 14.8-18.6) and rLOA ranging from 1.30-1.39 which is beyond the rLOA considered as unacceptable (i.e. 1.29) (Neville, & Atkinson, 1997). Whilst the ICC for PLV_{LF} showed questionable reliability, the CV ranged from 5.6-6.7% during the three stages demonstrating relatively low within-participant variability and hence may indicate the usability of this measure to ascertain perturbation in running gait in response to an experimental intervention.

The $H_{IN/EX}$ demonstrated moderate reliability for the first two RE stages with CV ranging from 8.8-9.3% indicating that analyses of hip joint kinematics in the transverse plane during running may be worthwhile. However, the reliability of $H_{AB/AD}$ was questionable (ICC<0.8) with values of 1.30-1.39 and 17.8-18.6%for the rLOA and CV, respectively, during the three stages. These results are not in agreement with findings by Noehren et al (2010) and Pohl et al (2010) showing a high reliability for hip joint kinematics in the frontal plane during running. These discrepancies in findings may be attributed to the type of technique used to apply retro-reflective markers. Noehren et al. (2010) showed that the use of a marker placement device substantially increased the repeatability of hip adduction compared to manual application. Pohl and colleagues (2010) showed high reliability in hip abduction/adduction by using technical clusters to track the markers during running. It has been reported that the retro-reflective markers as used in the current study are susceptible to larger displacement when applied on skin surfaces rather than on rigid clusters (Angeloni, Cappozzo, Catani, & Leardini, 1993; Cappozzo, Della Croce, Leardini, & Chiari, 2005). However, Miana et al. (2009) showed no significant differences in joint centre's positions when comparing the skin marker placement to the cluster method. Moreover, Ferber et al (2002) showed questionable between-day reliability for hip adduction during running when the cluster method was applied. Whilst the appropriate method of marker application appears to be inconclusive, caution must be taken when analysing hip joint kinematics in the frontal– and transverse planes.

In conclusion, the current study showed a high reliability in the majority of the selected kinematic variables with ankle and knee kinematics having greatest reliability at various running speeds with the application of a widely used marker system. Subsequently, these findings demonstrate that running gait analyses are worthwhile to determine the effectiveness of experimental interventions on RE amongst a heterogenous group of trained and moderately endurance trained runners.

Chapter 5

The reliability of isometric knee extensor torque amongst moderately trained and trained runners

This paper has been written in order to report the reliability of the custom-built dynamometer chair which was used to conduct maximal isometric voluntary contraction of the knee extensors during the series of studies undertaken as part of this project. Thus, this paper is substantially shorter than the other papers of this thesis and has not been written for publication purposes.

5.1 Introduction

The MVC test is a common method to determine muscle function and has been used extensively over the last 50 years (Wilson & Murphy, 1996). Force production during MVC tests is typically measured using various force transducers, including strain gauges, cable tensiometers and/or force platforms (Wilson & Murphy, 1996). The MVC test has been used to determine chronic responses to various training methods by examining the ability of the skeletal muscle to produce force (Iodice, Bellomo, Gialluca, Fano, & Saggini, 2011; Kvorning, Bagger, Caserotti, & Madsen, 2006) or to determine the level of muscular –fatigue and –damage as acute responses following exercises (Palmer & Sleivert, 2001; Skurvydas et al., 2006). Furthermore, MVC tests have been conducted on various muscle groups, such as knee extensor– and flexor muscles and elbow extensor– and flexor muscles (Colombo et al., 2000; Zech, Witte, & Pfeifer, 2008). Subsequently, it is essential that MVC tests employed are repeatable with minimal systematic, biological and technical biases.

Numerous studies have reported high reliability of MVC tests with ICC's ranging from 0.92-0.98 (Colombo, et al., 2000; Silvers & Dolny, 2011; Zech, et al., 2008). However, the protocol studies that have examined the reliability of MVC tests have predominantly reported ICC, which limits the applicability and comparability of the findings to a single measure. It has also been suggested that the sensitivity of ICC may be insufficient to detect comparisons on inter-individual differences and is therefore highly influenced by sample heterogeneity (Atkinson et al., 1998). The investigation of the reliability of MVC tests using CV, rLOA based on the method by Bland and Altman (1986) and the quantification of WD according to the measurement error (Neville & Atkinson, 1997) has not been reported in a single study. Such variations of statistical analyses will enhance the determination of assessing the adequacy of MVC measurements. Subsequently, the purpose of this study was to examine the reliability of MVC on a commonly examined muscle group, the knee extensors, amongst trained and moderately endurance trained cohorts obtained from Chapters 6, 7, 8 and 9 in the current project by using various reliability measures (i.e. ICC, CV, rLOA and WD).

5.2 Methods

Participants

The reliability of the MVC test was determined from 15–, 12– and 14 participants in Chapters 6, 7 and 8, respectively. Furthermore, the reliability of the MVC test for Chapter 9 was ascertained from two groups of 12 participants (n = 8 males and 4 females per group) which were evenly allocated into ST– and CON groups, respectively. The participants in Chapters 6, 7 and 8 consisted of trained and moderately trained male runners. The trained runners were middle to long distance runners (1,500 to 10,000m) and had all ran a 10,000m time trial less than 37 minutes. The moderately trained runners were undertaking high intense endurance training sessions at least twice.wk^{-1} from various sporting backgrounds. The participants' training background in Chapter 9 was similar to the moderately trained runners in the first three studies. The participants completed informed consent prior to conducting any testing procedures. All procedures in this study were approved by the Institutional Human Research Ethics Committee and were run in accordance with the Declaration of Helsinki.

Research design

The MVC tests were carried out across two days using a custom-built dynamometer chair (James Cook University, Australia). Knee extensor torque was measured by strapping the force transducer superior to the malleoli of the right leg. The participants performed three 6-second maximal isometric contractions with 1.5 minutes of rest in-between each contraction. The torque over the 6-second contraction was averaged and the largest value of the three contractions was selected. Knee extensor torque was collected and processed using custom-built software (James Cook University, Labview System, Australia). The force transducer was calibrated with a known weight prior to testing. Biological error was minimized by having participants refrain from high intensity physical activity for at least 24 hours prior to testing, refraining from caffeine and food intake for at least 2 hours prior to testing and conducting the MVC tests at the same time of day to control for circadian rhythm.

Statistical analyses

The data is expressed as mean ± standard deviation. All data was analysed using the Statistical Package for Social Sciences (SPSS, version 20, Chicago, IL). The test-retest reliability was analysed using the ICC (SPSS two-way mixed, 95% confidence intervals). The ICC values above 0.9 were considered high; above 0.8 but below 0.9 as moderate; and below 0.8 as questionable (Vincent, 2005). The measurement error was determined using intra-individual CV with associated 95% confidence interval (Hopkins, 2000) and measurement bias/ratio with 95% rLOA (Atkinson & Neville, 1998). Paired t-tests were used to determine differences in the MVC tests between the first and second testing sessions. The alpha level was set at 0.05. The WD in knee extensor torque was determined based on a nomogram for the estimation of the measurement repeatability error in accordance with the CV (Atkinson and Neville, 2006). The WD for hypothetical sample sizes of 10, 12, 15 and 30 were quantified as per the following linear equations:

1) $y = 1.5051x + 0.2384$

2) $y = 1.4576x + 0.2212$

3) $y = 1.1985x + 0.0817$

4) $y = 0.5974x + 0.0756$

Neville and Atkinson (1998) also suggested that an agreement ratio of */÷1.07 (i.e., 95% of ratios within 6% of the mean bias ratio) is regarded as excellent whereas */÷1.29 is unacceptable. Subsequently, delimitations will be decided by determining the level of agreement and its proximity to */÷1.06 in conjunction with the level of ICC and the magnitude of the CV and WD.

5.3 Results

For participants in Chapters 6, 7, 8 and 9, no significant differences were found in knee extensor torque between the first and second MVC tests ($P \geq 0.05$) (**Figure 5.1**). The ICC ranged from 0.76-0.93; CV ranged from 4.6-5.9; and rLOA ranged from */ 1.07-1.09 (**Table 5.1**). The WD for hypothetical sample sizes of 10, 12, 15 and 30 for participants in Chapter 6 ranged from 3.2-8.2%; for participants in Chapter 7 ranged from 3.6-9.1%; for participants in Chapter 8 ranged from 3.5-9.0%; and for the CON and ST groups ranged from 2.8-7.2% and 3.1-7.9%, respectively, in Chapter 9 (**Table 5.2**).

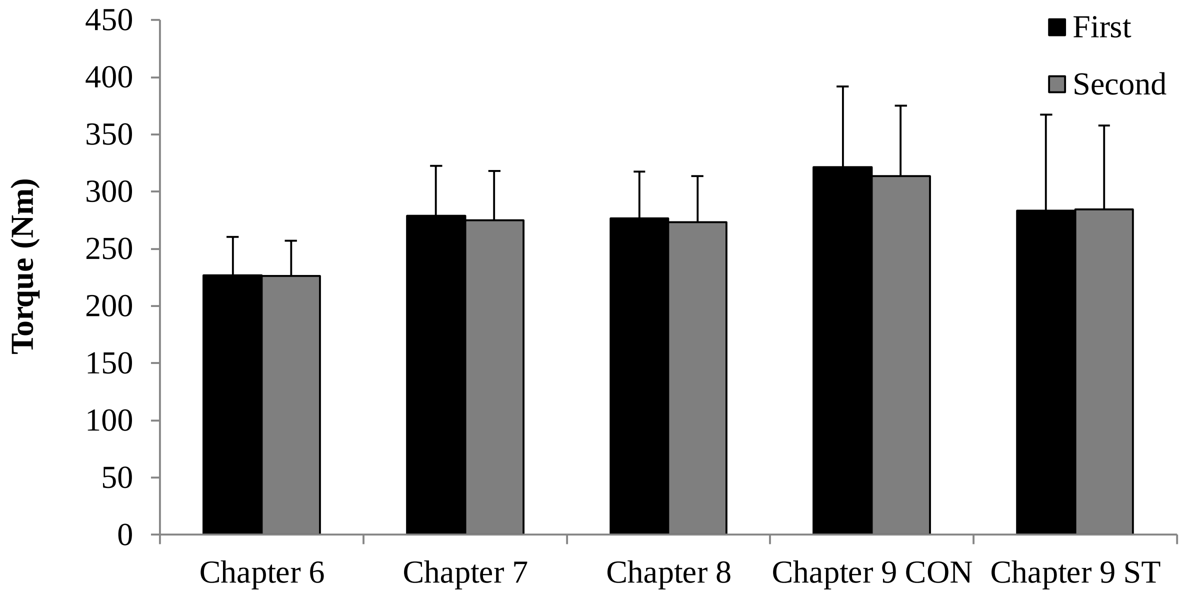

Figure 5.1. The knee extensor torque collected during the first and second maximal voluntary contraction tests for Chapters 6, 7, and 8 as well as for the concurrent training group (Chapter 9 CON) and the strength training group (Chapter 9 ST) in Chapter 9.

Table 5.1. Intra-class correlation coefficients (ICC) at 95% confidence interval (CI), measurement bias/ratio (log-transformed data) (*/÷ 95% ratio limits of agreement (rLOA)) and within-participant coefficient of variation at 95% CI of the two maximal voluntary contraction tests for Chapters 6, 7 and 8 as well as for the concurrent training group (Chapter 9 CON) and the strength training group (Chapter 9 ST) in Chapter 9.

	ICC (95% CI)	Measurement bias/ratio (*/÷ 95% ratio rLOA)	CV (95% CI)
Chapter 6	0.76 (0.37-0.92)	0.99 */ 1.09	5.3 (2.9-8.0)%
Chapter 7	0.80 (0.45-0.94)	1.01 */ 1.09	5.9 (3.0-9.0)%
Chapter 8	0.80 (0.45-0.93)	1.01 */ 1.09	5.8 (3.4-8.1)%
Chapter 9 CON	0.95 (0.82-0.98)	1.00 */ 1.07	4.6 (2.3-6.9)%
Chapter 9 ST	0.93 (0.78-0.98)	1.00 */ 1.08	5.1 (2.7-7.6)%

Table 5.2. Percentage of the worthwhile differences (WD) for the hypothetical sizes of 10, 12, 15 and 30 calculated in accordance with the within-participant coefficient of variation for the knee extensor torque for Chapters 6, 7 and 8 as well as for the concurrent training group (Chapter 9 CON) and the strength training group (Chapter 9 ST) in Chapter 9.

	Sample 10 (WD in %)	Sample 12 (WD in %)	Sample 15 (WD in %)	Sample 30 (WD in %)
Chapter 6	8.2	7.9	6.4	3.2
Chapter 7	9.1	8.8	7.2	3.6
Chapter 8	9.0	8.7	7.0	3.5
Chapter 9 CON	7.2	6.9	5.6	2.8
Chapter 9 ST	7.9	7.7	6.2	3.1

5.4 Discussion

The results showed that knee extensor torque measured by conducting MVC tests was reliable amongst trained and moderately trained runners that were incorporated in Chapters 6, 7, 8 and 9 in the current project.

The ICC values indicated moderate to high reliability for Chapters 7, 8 and 9. Whilst the ICC value suggested a questionable reliability for the MVC test during the study in Chapter 6, small differences in CV were found for each study, suggesting minimal measurement error. Hopkins (2000) reported that CV is a better indicator of reliability than retest correlations, in this case ICC, since retest correlations are sensitive to sample heterogeneity whereas CV can identify the reliability of the test without the need to have a sample that is strongly representative of a population. Given these differences in statistical quantification, Hopkins (2000) suggests that discrepancies in the level of reliability between CV and retest correlation is common. Therefore, the small CV reported by Chapters 6, 7, 8 and 9 for the MVC protocol despite variability in ICC suggests acceptable reliability.

In addition to minimal intra-individual variability, Chapters 6, 7, 8 and 9 showed rLOA of 1.07-1.09, suggesting that a torque of 250 Nm (i.e. a hypothetical measure) would fall within the margin of 272.5 Nm to 229.4 Nm. Whilst these measures cannot be compared to literature given that rLOA has not been examined specifically for maximal isometric knee extensor torque, a previous report has suggested that rLOA of 1.07 is considered excellent (Neville et al., 1997). Further, the WD ranged from 5.6-8.8% for samples sizes of 12 and 15 in Chapters 6, 7, 8 and 9 which are smaller than previous studies that have reported significant differences as a result of a particular intervention (Palmer & Sleivert, 2001; Zoladz et al., 2012).

The purpose of the current study was to examine the reliability of an isometric MVC test of the knee extensors. The results showed that maximal isometric torque of the knee extensors in the current study is reliable in accordance with the magnitude of intra-individual variability and the level of agreement between two repeated sessions.

Chapter 6

The acute effects of intensity and volume of strength training on running performance

Doma, K. & Deakin, G.B. (2012). The acute effects of intensity and volume of strength training on running performance. *European Journal of Sport Science,* 1-9, iFirst article.

6.1 Introduction

Strength training has been shown to improve RE and anaerobic running performance amongst athletes of various sporting backgrounds, including distance runners (Mikkola, et al., 2007), volleyball– (Davis, et al., 2008a), soccer– (Davis, et al., 2008a) and basketball players (Balabinis, et al., 2003). However, studies have also shown that concurrent training may impair VO_{2max} (Nelson, et al., 1990) and 4 km running time trial performance (Chtara, et al., 2005). It has been suggested that residual effects of fatigue generated by strength training may repetitively impair the quality of subsequent endurance training sessions and interfere with endurance adaptations (Chtara et al., 2005). Consequently, concurrent training necessitates exercise prescription in a strategic manner to minimize the transfer of fatigue between strength and endurance training sessions (Docherty & Sporer, 2000). Indeed, reports have shown that sub-maximal cycling performance (Deakin, 2004), sub-maximal running performance (Palmer & Sleivert, 2001) and maximal running performance (Marcora & Bosio, 2007) are attenuated 3–, 8– and 24 hours post strength training, respectively. However, studies have also shown that sub-maximal running performance (Marcora & Bosio, 2007; Paschalis, et al., 2005; Scott, et al., 2003; Vassilis, et al., 2008) is not affected 24-48 hours following strength training.

Accordingly, strength and endurance training sessions may be incorporated on alternate days to limit the impact of strength training on sub-maximal endurance performance. However, such concurrent training programs would not be applicable to athletes undertaking endurance training sessions on consecutive days through the week. In addition, continually performing endurance training sessions at sub-maximal intensities over the course of a training program would limit optimal endurance adaptations (Issurin, 2010). In order to understand the mechanisms attributing to the impact of strength training on endurance performance, it is essential to systematically examine various strength training variables (e.g. contraction velocity, whole body versus lower body only strength training, and intensity of strength training) on endurance performance on the same day. Such findings would enable the formulation of strength training programs that would minimise acute detrimental effects on endurance performance.

Studies have reported that resistive-type exercises performed with fast compared to slow eccentric contractions significantly reduced MVC post exercise (Chapman, et al., 2008). Subsequently, a strength training session consisting of exercises performed with slow eccentric contractions may limit potential carry-over effects of fatigue from strength to endurance training sessions within a concurrent training program. In conjunction with controlling the contraction velocity, the degree of subsequent attenuation of endurance performance may be affected by adjusting the intensity (i.e. high versus low) and volume (i.e. number of exercises performed) of a preceding strength training session. Indeed, Deakin (2004) examined the acute effects of altering the intensity (i.e. high versus low intensity) and volume (i.e. whole body versus lower body only) of exercises during strength training sessions on endurance performance. Sub-maximal cycling performance was analysed three hours following HW, HL and LL strength training sessions performed at a self-selected pace. The findings showed that both HW and HL sessions caused detrimental effects whereas the LL session had no effect on sub-maximal cycling performance. In addition, the HW session had a more prominent effect on sub-maximal cycling performance than the HL session.

In light of the above, it appears that the impact of strength training on MVC and sub-maximal endurance performance is dependent on the eccentric contraction velocity of strength training and the intensity of strength training, respectively. Furthermore, strength training exercises that engage a greater number of muscle groups appear to have a more profound effect on sub-maximal endurance performance. However, it is unknown whether changes in strength training –volume (i.e. whole body versus lower body only) and –intensity (i.e. high versus low) with slow eccentric contractions would affect sub-maximal and/or maximal running performance. Examining the acute effect of altering the intensity of strength training with slow eccentric contractions on running performance may give further insight on the dynamics of exercise-induced fatigue and recovery between strength and endurance training sessions.

The purpose of the present study was to investigate the effect of altering the intensity (i.e. high intensity versus low intensity) and volume (i.e. whole body versus lower body only) of strength training sessions performed with slow eccentric contractions on sub-maximal running performance (i.e. RE) and maximal running performance (i.e. TTE) 6 hours post. It was hypothesised that the various modes of strength training with slow eccentric contractions would not affect running performance with a 6-hour recovery period.

6.2 Methods

Participants

A group of 15 trained and moderately trained male runners (mean ± standard deviation: age 23.3 ± 5.0 years; height 1.8 ± 0.1 m; body mass 76.1 ± 10.0 kg; VO_{2max} 63.9 ± 6.5 $mL.kg^{-1}.min^{-1}$) who had not undertaken high intensity strength training sessions (i.e. < 10 repetition maximum) during the last 6 months participated in the study. The trained runners were middle to long distance runners (1500-10,000 m) who were running at least 50 $km.week^{-1}$ and had an average VO_{2max} of 69.7 ± 4.1 $mL.kg^{-1}.min^{-1}$ which is similar to a group of competitive middle– and long distance runners according to a previous report (Saunders et al., 2006). The moderately endurance trained runners were covering approximately 5-10 $km.week^{-1}$ and had various sporting backgrounds (e.g. soccer, basketball and cricket). The participants did not have experience in strength training or have not undertaken high intensity strength training for the past 6 months. Each participant completed informed consent before taking part in any testing procedures. All procedures in this study were approved by the Institutional Human Research Ethics Committee and were run in accordance with the Declaration of Helsinki.

Research Design

The current study was carried out across 5 weeks consisting of a familiarization session with a 6 RM assessment and a VO_{2max} test during the first week. The second week consisted of two RE tests for familiarity purposes with data being collected during the second RE test for baseline (Base-RE). During the last three weeks, HW, HL and low intensity whole body strength training sessions (LW) were carried out in randomised order. Maximal voluntary contraction tests were conducted before and after each strength training session and the RE tests carried out 6 hours following the strength training sessions. Technical and biological variations were controlled by conducting the strength training sessions and post RE tests at the same time of the day and at the same time of the week, requiring participants to maintain their dietary– and training habits, wearing the same shoes for every test, refraining from caffeine– and food intake for at least 2 hours prior to testing and refraining from high intense physical activity for at least 24 hours prior to testing.

Six repetition maximum assessment

The 6RM assessments included incline leg press (Maxim MF701, South Australia, Australia), bench press (Maxim MF-710, South Australia, Australia), and bench pulls using a custom-built flat bench (James Cook University, Australia). Determination of 6RM assisted in the development of the intensity of the HW and HL sessions and the intensity of the LW session by quantifying the work done to equate the training volume (Thornton & Potteiger, 2002). Each exercise was performed using a one second concentric contraction and a four second eccentric contraction duration (Dolezal, Potteiger, Jacobsen, & Benedict, 2000) synchronised with a metronome. Prior to the 6RM assessments, participants warmed up with 15 repetitions of each strength training exercise with 50% of body weight for the incline leg press and 30% body weight for bench press and bench pulls, respectively. There was 5 minutes rest between each attempt of each strength training exercise and each participant's 6RM of each exercise was successfully determined within three attempts.

Maximal oxygen consumption test

A progressive warm-up was completed by walking at 5 $km.h^{-1}$ for 5 minutes then jogging at 8–, 10–, and 12 $km.hr^{-1}$ for 1 minute, respectively, on a treadmill (Quinton Q65, USA). During the VO_{2max} test, the participants underwent continuous incremental running at 0% gradient starting at 12 $km.h^{-1}$ and increasing the speed by 1.5 $km.h^{-1}$ every two minutes until exhaustion (Doma, Deakin, & Sealey, 2012). Heart rate (HR, Polar RS800, New York, USA) and RPE (Borg's 6-20 scale) were recorded every minute with respiratory parameters collected continuously with a Cosmed $K4b^2$ gas analyser (Cosmed, Rome, Italy). The Cosmed system was calibrated using certified alpha gas mixtures of 16% oxygen and 4% carbon dioxide concentration and a three litre calibration syringe. Breath-by-breath respiratory measures were averaged every 15s. The highest average VO_2 over a 60 s interval was accepted as VO_{2max} when the participant met three of the following four criteria: VO_2 plateau, RPE > 17, respiratory exchange ratio (RER) > 1.1, peak HR > 90% of age predicted HR (Midgley, McNaughton, Polman, et al., 2007).

Running economy test

The RE protocol was a three-stage incremental test running at 70–, 90– and 110% of VT_2, respectively (Doma, Deakin, Leicht, & Sealey, 2012). The duration of the first two stages was 10 minutes each with the last stage to exhaustion in order to determine TTE. There were two minutes rest between each stage. The VT_2 for each participant was determined from the VO_{2max} test by ascertaining the inflection point of ventilation with respect to carbon dioxide production on a scatter diagram (Doma, Deakin, & Sealey, 2012). The VT_2 was used due to its greater reliability (Neder & Stein, 2006) and ability to induce fatigue earlier than the first ventilatory threshold (Kerr, et al., 2008). Variables indicating the physiological cost of running included C_R where VO_2 is expressed relative to body mass to the power of 0.75 per metre ($mL.kg^{-0.75}.m^{-1}$), RER and HR. The expression of C_R was selected accordingly as it has been reported to minimize between-participant variability (Helgerud, et al., 2001). These physiological variables were averaged during the last 5 minutes of the first two stages to ensure that the participants reached steady-state running and averaged during the last minute of TTE to determine peak values. Steady-state was defined when the change in VO_2 was <10% per minute (Reeves, et al., 2004). The RPE was collected on the 9th minute of the first two stages and at the completion of the RE test during TTE.

Maximal voluntary contraction test

The MVC tests were conducted on a custom-built dynamometer chair (James Cook University, Australia). Three maximal isometric contractions of the knee extensor muscles were performed with each contraction held for 6 seconds and 1.5 minutes rest between each contraction (Riley, Maerz, Litsey, & Enoka, 2008). The dynamometer chair was adjusted so that the knee joint rested at 110° and a strap attached to a force transducer was wrapped superior to the medial and lateral malleoli to measure torque. The dynamometer chair was calibrated by placing a known weight on the force transducer. Torque was calculated by averaging the values over the 6-second contraction with the largest torque being reported amongst the three contractions.

Strength training session

Prior to the strength training exercises, the participants warmed up with the procedure identical to that used for the 6RM assessment. The type of exercises, load lifted and the recovery period between sets and exercises for the HW, HL and LW sessions are presented in **Table 6.1**. The cadences of each repetition of the strength training exercises were performed with the method identical to the 6RM assessment. A three minute recovery was provided between each of the strength training exercises.

Table 6.1. The type of exercises, intensity, volume and the recovery period between sets (RBS) during high intensity whole body (HW), high intensity lower body only (HL) and low intensity whole body (LW) strength training sessions

	HW		HL		LW	
Exercises	Sets x Reps	RBS	Sets x Reps	RBS	Sets x Reps	RBS
Lower body						
Incline leg press	6 x 6	3 minutes	6 x 6	3 minutes	6 x 20	1.5 minutes
Upper body						
Bench press	4 x 6	3 minutes			4 x 20	1.5 minutes
Bench pulls	4 x 6	3 minutes			4 x 20	1.5 minutes

Statistical power calculation

We previously tested the measurement error for the C_R, RPE and TTE during the RE test and torque production amongst trained and moderately endurance trained men (n = 14) and showed within-participant CV of 2.5–, 3.6–, 9.2– and 8.3%, respectively. According to a nomogram for the estimation of measurement error (statistical power at 90%) with the use of within-participant CV (Atkinson & Nevill, 2006), WD for the C_R, RPE, TTE and torque production were found to be 2.5–, 4.5–, 11.5– and 10% for a sample size of 15. These percentage differences are smaller than previous reports that have shown significant differences in the oxygen cost of running (Palmer & Sleivert, 2001), TTE (Farzad et al., 2011), RPE (Doherty, Smith, Hughes, & Davidson, 2004) and torque production (Palmer & Sleivert, 2001) as a result of a particular intervention.

Statistical analyses

All data are expressed as mean ± standard deviation and were analysed using the Statistical Package for Social Sciences (SPSS, version 18, Chicago, IL). A one-way repeated measures analysis of variance (ANOVA) was used to analyse differences in VO_2, RER, HR and TTE between the RE tests and a two-way (session x time) with one between-participant factor (exercise order) repeated measures ANOVA was used to determine differences in torque generated from the MVC tests. In order to determine the location of the difference, pairwise comparisons with Bonferroni's adjustments were used. To determine whether the degree of perturbation on running performance as a result of strength training was associated with the level of fitness, relationships between the VO_{2max} and the percentage difference in performance variables (i.e. C_R and/or TTE) that showed a significant difference between Base-RE and the RE tests following HW, HL and LW sessions were examined using Pearson's product moment correlation coefficient. The alpha level was set at 0.05.

6.3 Results

There were no significant differences between the Base-RE and the RE tests following HW, HL or LW sessions for C_R, RER, HR and RPE during the three stages of the RE tests ($P \geq 0.05$) (**Figure 6.1**). However, TTE during the RE tests following HW and HL sessions were significantly less than Base-RE ($P < 0.05$) although no significant differences were found in TTE between Base-RE and the RE test following the LW session ($P \geq 0.05$) (**Figure 6.2**). Torque at Pre St and Pre RE were significantly greater than Post St for the LW ($P < 0.05$ and 0.01, respectively) and HL ($P < 0.05$) sessions (**Figure 6.3**). There were no significant differences between time points for peak and average torque during the HW session ($P \geq$

0.05). No significant relationship ($P \geq 0.05$) was found between the participants' VO_{2max} and the percentage differences in TTE between Base-RE and the RE tests following HW, HL and LW sessions.

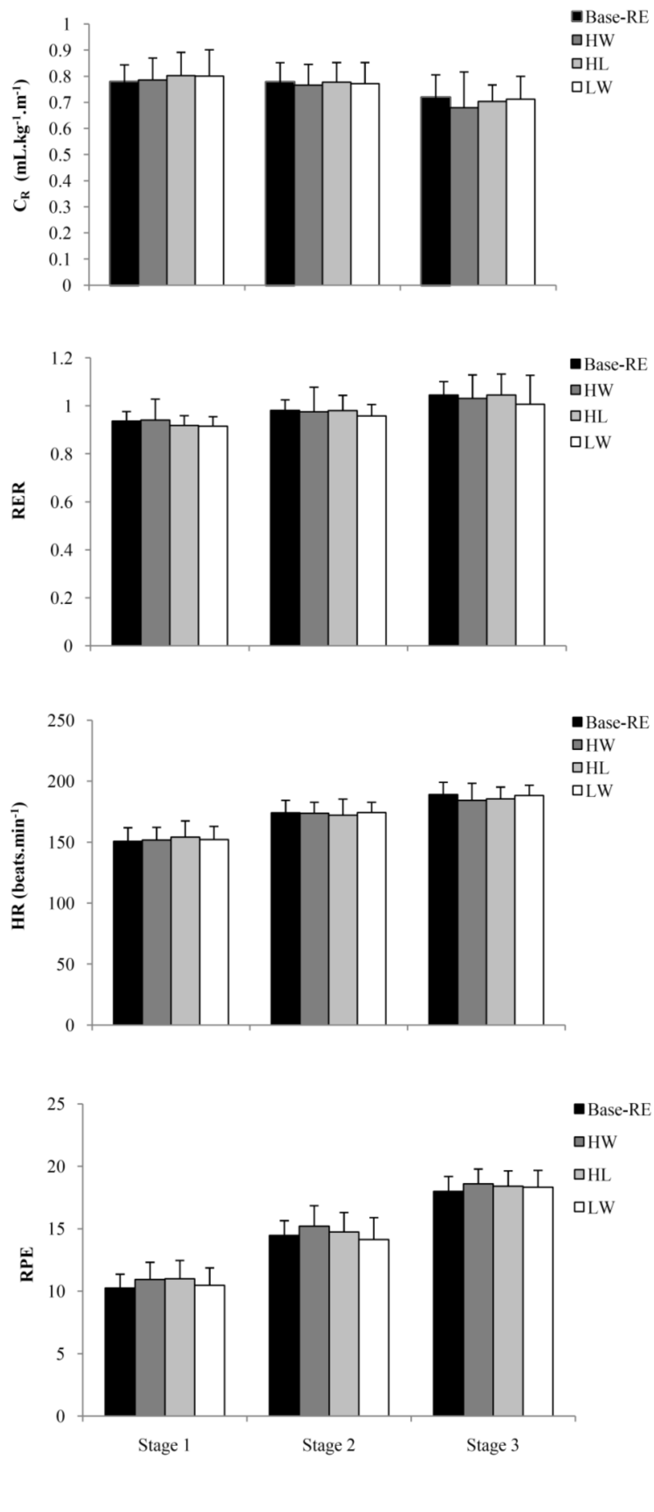

Figure 6.1. The oxygen cost of running (C_R), respiratory exchange ratio (RER), heart rate (HR) and rating of perceived exertion (RPE) during the running economy test at baseline (Base-RE) and the running economy tests following high intensity whole body (HW), high intensity lower body only (HL) and low intensity whole body (LW) strength training sessions at Stages 1, 2 and 3

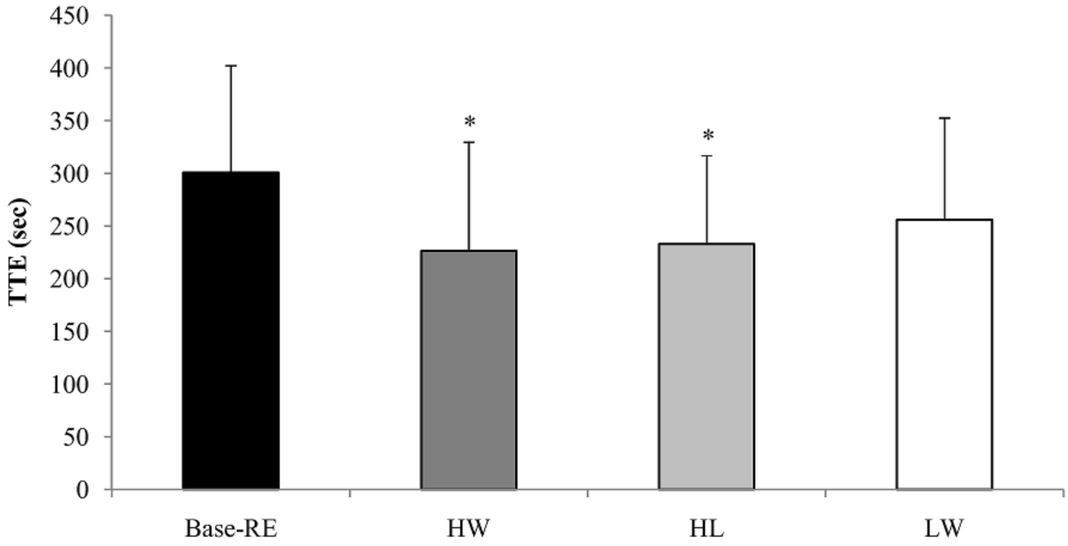

Figure 6.2. Time-to-exhaustion (TTE) during the baseline running economy test (Base-RE), and the running economy tests following high intensity whole body (HW), high intensity lower body only (HL) and low intensity whole body strength training (LW) sessions

* significantly different from Base-RE ($P < 0.05$)

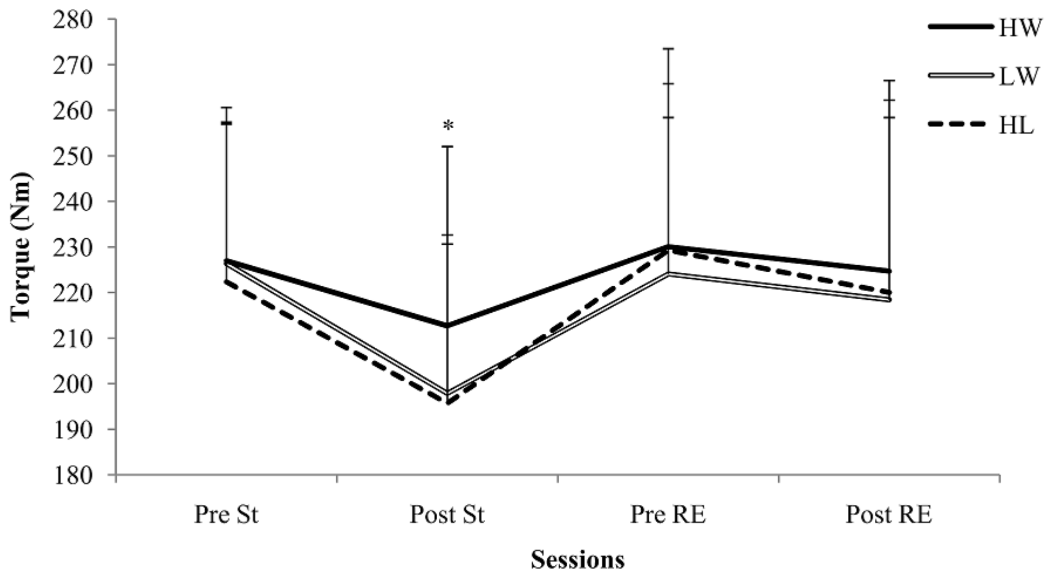

Figure 6.3. Torque measured prior to (Pre St) and following (Post St) the high intensity whole body (HW), high intensity lower body only (HL) and low intensity whole body (LW) strength training sessions; prior to (Pre RE) and following (Post RE) the running economy (RE) tests

* HL and LW significantly different from Pre St ($P < 0.05$)

6.4 Discussion

This study is the first to examine the effects of altering the intensity and volume of strength training exercises with slow eccentric contractions on running performance on the same day. The findings showed that RE (i.e. C_R during the first two stages of the RE tests) and muscle force generation capacity (MFGC) were not affected 6 hours following HW, HL and LW sessions. However, TTE was significantly less following HW and HL sessions which reject our hypothesis stating that strength training exercises performed with slow eccentric contractions would not affect running performance with a 6-hour recovery period. The comparable effects on RE between Base-RE and the RE tests following HW, HL and LW sessions are in contrast to results obtained by Palmer and colleagues (2001) where RE was impaired 8 hours following a whole body strength training session involving exercises performed at 8RM using a self-selected pace method. The discrepancies in the findings by the current study and that by Palmer et al (2001) may be attributed to strength training exercises performed at different contraction velocities. Chapman et al (2008) demonstrated greater reduction in isometric and dynamic torque production and a greater level of CK following fast compared to slow velocity eccentric exercise of the elbow flexors. Furthermore, it has been reported that traditional strength training exercises performed with fast compared to slow contraction velocities at 12RM caused significantly greater attenuation in strength (i.e. 1RM) and power (i.e. counter movement jump) indices for up to 48 hours post (Ide et al., 2011). However, Ide and colleagues (2011) also altered the contraction velocity of concentric contractions. The acute effects of altering eccentric contraction velocity whilst maintaining concentric contraction velocity, similar to that incorporated in the current study, on muscle performance following traditional strength training is unknown and therefore warrants investigation. Nonetheless, it appears that the level of decrement in muscular performance appears to be greater following resistance-type exercises executed with fast– compared to slow eccentric contractions.

The non-significant effect on RE following strength training in the current study may also be due to the minimal number of strength training exercises performed. Palmer and colleagues (2001) incorporated five upper and lower body strength training exercises and demonstrated detrimental effects on RE with an 8 hour recovery period whereas the current study only consisted of three exercises for the whole body strength sessions with a 6 hour recovery period. Previous reports have shown that strength training sessions with greater volume induces greater fatigue through neural (Häkkinen, 1993) and metabolic (Ratamess et al., 2009) responses. Whilst Deakin (2004) utilised strength training protocols equivalent to the present study and found that cycling efficiency was impaired following a HW session consisting of only three exercises, the author only incorporated a three hour recovery period. Subsequently, HW, HL and LW sessions may not have affected sub-maximal endurance performance in the present study due to fewer strength training exercises and greater recovery incorporated between the strength training sessions and the RE test than that previously reported (Deakin, 2004; Palmer et al., 2001).

No relationship was found between VO_{2max} and the reduction in TTE in the current study, indicating that the decrement in running performance as a result of strength training was not dependent on the participants' level of fitness. This attenuation in running performance with maximum effort (i.e. TTE) following the HW and HL sessions is in agreement with the findings by Marcora and Bosio (2007) who showed no effect on RE although time-trial performance increased 24 hours following EIMD (i.e. repeated vertical jump). Furthermore, Chen, Nosaka, Lin, Chen and Wu (2009) showed an increase in the oxygen cost of running above AT (i.e. 80-90% of VO_{2max}) with no effect found below AT 24 hours following downhill running, indicating that the acute effect of strenuous exercise appears to augment when running performance is assessed at higher intensities.

Chen et al (2009) postulated that the attenuation in RE at greater running speeds may be due to differences in muscle fibre recruitment patterns. Indeed, reports have shown that type 1 fibres are predominantly recruited at running intensities below AT and that a greater number of type 2 fibres are recruited at running intensities above AT (Abernethy, et al., 1990; Gollnick, et al., 1974). Given that intense eccentric contractions, which is a large component of strength training, have shown to cause greater muscle damage to type 2 than to type 1 muscle fibres (Friden, Sjostrom, & Ekblom, 1983), the ability to recruit type 2 muscle fibres during running above AT may have been compromised and consequently hampered running performance.

The present investigation showed that TTE was significantly less following HW and HL sessions although there were no changes following the LW session. This confirms the results obtained by Deakin (2004) where HW and HL sessions increased the physiological cost of cycling three hours post although no effects were found following a session consisting of LL strength training. Whilst Deakin (2004) showed detriment in sub-maximal cycling performance as opposed to running at maximum effort in the current study, our findings and that by Deakin (2004) demonstrate a greater residual effect on endurance performance following high intensity strength training regardless of contraction velocities. Indeed, Thornton and Potteiger (2002) reported greater EPOC following high– compared to low intensity strength training with equal training volume. The authors suggested that a greater number of motor units may have been recruited with heavier loads, resulting in disturbances of the metabolic system. Subsequently, HW and HL sessions may have impaired TTE in the current study due to a greater amount of working muscle mass compared to the LW session.

Whilst TTE was significantly less following HW and HL sessions, maximal isometric torque returned to baseline 6 hours post. These findings may suggest that decrement in running performance following strength training may not have been due to neuromuscular fatigue. However, given that running involves dynamic movements and thus requires the recruitment of multiple muscle groups, drawing conclusions regarding running performance solely based on isometric contractions of the knee extensors may be premature. Previous studies (Beck et al., 2004; Coburn et al., 2004) have suggested that additional motor units are recruited during isokinetic contractions whereas the number of active motor units and their firing rates increases with an increase in isometric force, indicating that different motor unit recruitment strategies are used between contraction types. In addition, it has been reported that mechanomyographic amplitude versus isometric torque relationship differs between knee angles of 25°, 50°, and 75° of knee flexion (Ebersole et al., 1999), demonstrating that motor unit firing rate and recruitment patterns during isometric contractions may be dependent on knee angle. Subsequently, maximal isometric torque in the current study may have differed if examined at various knee angles.

In summary, the findings in the current study demonstrated no effects on RE although TTE was significantly reduced 6 hours following HW and HL strength training sessions. The minimal effect on RE may have been due to the strength training exercises performed with slow eccentric contractions (Chapman et al., 2008) or as a result of HW and LW sessions consisting of only three exercises as strength training sessions with greater volume have shown to attenuate RE (Palmer et al., 2001). Given that contraction velocity was standardized in the current study, future research could standardize intensity and/or volume and alter contraction velocity of strength training to determine the effect of fast versus slow eccentric contractions on running performance. The negative impact on TTE may be attributed to changes in muscle fibre recruitment patterns; however, this rationale requires validation by analysing maximal isometric torque of the hip– and knee flexors and extensors at various joint angles. Collectively, these findings contribute to the body of knowledge regarding the acute effects of concurrent training.

From a practical standpoint, running at intensities under AT may be carried out with minimal detriment in performance following strength training sessions incorporated in the current study with a recovery period of at least 6 hours amongst trained and moderately endurance trained men who have not undertaken high intensity strength training sessions for at least 6 months. However, given that RE is a predicted measure for long distance running performance (Saunders, et al., 2004a), coaches are advised to experiment with the strength training methodology as described in the current study prior to finalising a concurrent training program for their athletes. Whilst LW session caused no significant effect on TTE, given that there was a 15% reduction, caution should be taken when undertaking high intense running sessions 6 hours following HW, HL and LW sessions. In addition, a 6 hour recovery period may not be sufficient following the current strength training sessions for untrained individuals.

Chapter 7

The effects of combined strength and endurance training on running performance the following day

Chapter 6 showed that strength training did not affect RE and that MVC returned to baseline values 6 hours post. These findings may be due to 1) strength training exercises performed with deliberately slow eccentric contractions, 2) a strength training session consisting of only one lower extremity strength training session (i.e. incline leg press), 3) the impact of exercise-induced fatigue on running performance was limited to a single mode of training session (i.e. strength training) on the same day, 4) running performance variables were limited to RE and TTE. Subsequently, this study (i.e. Chapter 7) was structured based on several points highlighted in Chapter 6. Firstly, the volume of the strength training session was increased by incorporating a greater number of lower extremity strength training exercises (i.e. leg press, leg extension and leg curls). Secondly, the participants performed the exercises at a self-selected pace to allow the execution of faster eccentric contractions and to replicate a commonly prescribed strength training session. Thirdly, kinematics of the lower extremity were captured to allow for a more robust running performance analyses. Finally, a moderate to high intensity endurance training session was conducted 6 hours following the strength training session to examine the impact of combining the two modes of training on running performance the following day.

Doma, K., & Deakin, G.B. (2012). The effects of combined strength and endurance training on running performance the following day. *International Journal of Sport and Health Sciences,* In Press.

7.1 Introduction

Combining strength and endurance training sessions in the one training program, referred to as concurrent training (Hickson, 1980), has been shown to interfere with strength development (Leveritt et al., 1999). This interference has been suggested to occur due to preceding endurance exercises compromising optimal force production during subsequent strength training sessions, known as the "acute hypothesis" (Leveritt et al., 1999). Indeed, reports have shown that endurance training impairs maximal voluntary contraction (MVC) for 6 hours post training (Bentley et al., 2000), indicating that endurance exercises may cause detrimental effects on strength training performance. However, studies have also shown that strength training reduces MVC for over 48 hours (Brentano and Kruel, 2011; Hakkinen et al., 1988), suggesting that endurance performance may be impaired in the hours following a strength training session. Subsequently, chronic endurance development could be compromised if the quality of each endurance training session is interfered due to preceding strength training sessions. Examining the acute effects of strength training (e.g. several hours post training) on endurance performance may shed light on factors attributing to the possible interference of chronic endurance development during concurrent training.

Studies have reported that strength training impaired running economy (RE) 8 hours post (Palmer and Sleivert, 2001) and compromised running time-trial performance (Marcora and Bosio, 2007) and repeated sprint ability (Twist and Eston, 2005) 24 hours post. In contrast, studies have shown no effect on RE 24 hours following strength training despite increases in creatine kinase and muscle soreness (Marcora and Bosio, 2007; Paschalis et al., 2007). Collectively, these findings suggest that strength training may impair sub-maximal endurance performance on the same day yet cause no affect the following day, or affect maximal endurance performance the following day. However, these studies (Marcora and Bosio, 2007; Paschalis, et al., 2007; Twist and Eston, 2005) collected endurance performance measures following a single training session. To date, the effect of combining the two modes of exercises on the same day and their effect on various performance measures the following day remains unclear.

Studies have reported that MVC was compromised 6 hours post endurance training (Bentley et al., 2000) and 24 hours post strength training. Therefore, it is presumable that performing strength and endurance training sessions 6 hours apart on the same day will impair various performance measures the following day. However, sub-maximal endurance exercises have been shown to accelerate recovery following strenuous exercises due to an increase in blood flow (Faude et al., 2009). Subsequently, an endurance training session performed after a strength training session with several hours of recovery may function as a buffer and limit the impact of fatigue on endurance performance the following day. Furthermore, an overnight passive recovery period (e.g. 16-24 hours) may provide sufficient recovery from performing strength and endurance training sessions on the same day. This has been highlight by previous studies where full recovery from high intensity endurance exercises occurred within 24 hours (Bentley, et al., 2000) and that no deletrious effects on sub-maximal running performance was found 24 hours following strength training (Marcora and Bosio, 2007).

The purpose of the current study was to two fold. First, to examine the acute effect of a strength training session on various performance measures (i.e. MVC, RE, running time-to-exhaustion and kinematics) performed 6 hours later. Second, examine the combined effect of performing strength and endurance training sessions on the same day on performance measures the following day. It was hypothesised that attenuation in running performance will occur 6 hours following strength training as well as the following day as a result of undertaking both strength and endurance training sessions on the same day.

7.2 Methods

Participants

A group of 12 trained and moderately trained male runners (mean ± standard deviation: age 23.4 ± 6.4 years; height 1.8 ± 0.1 m; body mass 75.0 ± 8.2 kg; VO_{2max} 62.5 ± 6.0 $mL.kg^{-1}.min^{-1}$) who had not undertaken lower extremity strength training exercises for two months took part in the study. The TR were middle to long distance runners (1500-10,000 m) covering at least 50 km. $week^{-1}$ and had all run a 10,000 m time trial within 35 minutes during the last 6 months. The METM were covering 5-10 km. $week^{-1}$ in addition to their various sporting backgrounds.). The participants did not have experience in strength training or have not undertaken high intensity strength training for the past 6 months. Each participant completed informed consent before taking part in any testing procedures. All procedures in this study were approved by the Institutional Human Research Ethics Committee and were run according to the Declaration of Helsinki.

Research design

The study was conducted across 5 weeks. The first four weeks were used as preparation and the experiments were conducted during the fifth week (**Figure 7.1.**). During the first week, a familiarisation session and a VO_{2max} test was conducted. In addition to familiarity purposes, a 6RM assessment was conducted according to previous guidelines (Baechle & Earle, 2008) during the familiarisation session. The VO_{2max} test was a continuous incremental running protocol to exhaustion on a treadmill as described previously (Doma, Deakin, Leicht, & Sealey, 2012). During the second week, two RE tests were carried out for familiarity. The data collected during the second RE test was used as Base-RE. Two strength sessions were undertaken during the third and fourth week as washout to limit early on-set of neuromuscular adaptations (Marshall, McEwen, & Robbins, 2011). During the strength training session, exercises were performed in the order of leg press (Maxim MF701, Australia) for 6 sets and leg curls and leg extensions (Avanti, B253 Olympic Bench, Australia) for four sets at 6RM, respectively, with three minutes of rest in between each set and exercise. In the last week, a strength session and a running session were conducted 6 hours apart with a RE test (Post-RE test) 24 hours following the strength session. The running session was treated as an endurance training session which was separate from the RE test in order to investigate the accumulation effect of strength and endurance training on running performance (i.e. RE test) over two consecutive days. All RE tests were conducted at the same time of day. Maximal voluntary contraction was also measured prior to and following the strength session, running session and Post-RE test.

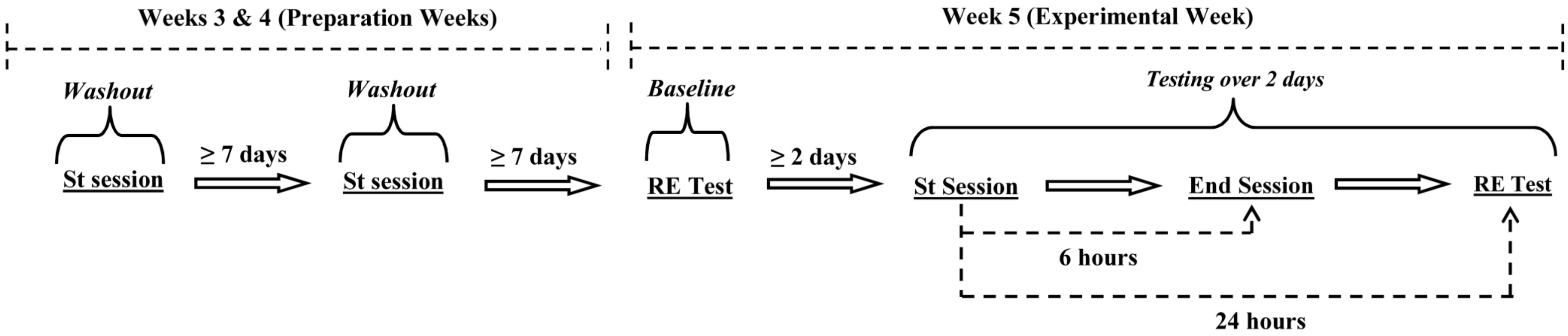

Figure 7.1. Schematic of the research design including the strength training (St) session, running economy (RE) test and the running (End) session.

Running session

Running sessions were performed following a progressive warm-up by walking on the treadmill for 5 minutes then jogging at 8–, 10– and 12 km.hr^{-1} for one minute, respectively. The running session consisted of three incremental stages with intensities set at 70–, 90– and 110% of the VT_2 and two minutes of rest between each stage. The first two stages consisted of two 10 minute stages with four 2 minute intervals during the last stage with a work to rest ratio of 1:1. During the first two stages, C_R, RPE and lower extremity kinematics were collected. The C_R was calculated such that VO_2 was expressed relative to body mass to the power of 0.75 per metre (mL.kg$^{-0.75}$.m^{-1}) as this has been shown to minimize inter-individual variability (Doma, Deakin, Leicht, & Sealey, 2012). In addition, C_R was averaged during the last 5 minutes of the first two stages to ensure that the participants reached steady-state running (Doma, Deakin, Leicht, & Sealey, 2012). Steady-state was defined when the change in VO_2 was <10% per minute (Reeves, et al., 2004). The VT_2 was determined from the VO_{2max} test by ascertaining the inflection point of ventilation with respect to carbon dioxide production on a scatter diagram (Neder & Stein, 2006). The RPE was collected during the 9th minute of the first two stages.

Running economy test

The Base-RE and Post-RE tests were conducted following a warm-up identical to the running session. The RE tests consisted of three incremental stages running at 70–, 90–, and 110% of VT_2, respectively (Doma, Deakin, Leicht, & Sealey, 2012). There were two minutes of recovery between the three stages. The C_R, RPE and lower extremity kinematics were collected during the first two stages identical to that during the running sessions. However, whilst the last stage was treated as an interval period for the running session, the participants ran to exhaustion during the RE test to determine TTE. Rating of perceived exertion was collected every minute during TTE and the RPE of the middle time points during the shortest TTE of a given RE test was used for comparisons (e.g. if TTE for a given participant was 5 minutes for Post-RE, then the RPE for the third minute of Post-RE was compared with the third minute of Base-RE). Peak C_R was also collected during TTE. The first two stages of the running session and RE tests were standardised to compare running performance variables between the Base-RE test, running session and Post-RE test whilst allowing the running session to contribute as an endurance training session.

Kinematic Analyses

Running gait was captured at 9 minutes 30 seconds of the first two stages of Base-RE, running session and Post-RE test. At least 10 strides of kinematic data were recorded for each motion capture at 100Hz using a 3-D 8-camera optical motion analysis system (VICON Motion Systems, Oxford, UK). The optical cameras were statically calibrated for each testing session and ensured an image error of < 0.15pixels. The measuring volume covered 1.5m x 3m x 2m (width, length, height). The pelvis, thighs, shank and the feet were captured using 16 retro-reflective markers (14 mm diameter) placed by a single well trained investigator according to Nexus Plug-in Gait Model. Running gait parameters included A_{ROM}, KF_S, KF_{AS} and H_{ROM} in the sagittal plane. Kinematic parameters were limited to 2-dimensions as the reliability of lower extremity kinematics has been reported to be questionable in the transverse and frontal planes (Doma, Deakin, & Sealey, 2012). Raw kinematic data were filtered using Woltring filtering routine with the mean squared error at 20mm^2 based on residual analyses (Winter, 2008).

Maximal voluntary contraction test

A custom-built dynamometer chair (James Cook University, Australia) was used to conduct MVC tests. Three maximal isometric contractions of the knee extensor muscles were performed for 6 seconds with 1.5 minutes rest between each contraction (Doma & Deakin, 2012) whilst the knee joint was positioned at 110°. Torque was calculated by averaging the values over the 6-second contraction with the largest torque being reported amongst the three contractions.

Statistical analyses

All data are expressed as mean ± standard deviation. A one-way analysis of variance was used to determine differences in C_R, RPE and lower extremity kinematics (i.e. A_{ROM}, KF_S, KF_{AS} and H_{ROM}) between the Base-RE test, running session and Post-RE test and to analyse differences in torque between the 6 different time points (i.e. prior to and following the strength session, running session and Post-RE test) of the MVC tests and pairwise comparisons with Bonferroni's adjustments. Paired T-tests were conducted to analyse the difference in TTE between Base-RE and Post-RE tests. Pearson's product moment correlation was used to analyse the relationship between the running performance variables (i.e. C_R, RPE and TTE), running kinematics and torque. Data analyses were conducted using the Statistical Package for Social Sciences (SPSS, version 18, Chicago, IL) with the alpha level at 0.05.

Sample size

Based on an in-house reliability study of the RE test and MVC test used in the current study, the within-subject coefficient of variation (CV) for C_R, RPE, TTE and torque production amongst trained and moderately endurance trained men (n = 14) were 2.5-, 3.6-, 9.2- and 8.3%, respectively (Doma, Deakin, Leicht, & Sealey, 2012). With the use of the estimation of measurement error based on a nomogram and CV (statistical power of 90%) (Atkinson & Nevill, 2006), the percentage worthwhile differences for the current sample size (n = 12) for C_R, RPE, TTE and torque production were found to be 3.9-, 5.5-, 13.6- and 12.3%, respectively. These worthwhile differences are smaller than previous studies that have shown significant differences in RE (Palmer & Sleivert, 2001), RPE (Doma, Deakin, Leicht, & Sealey, 2012), TTE (Doma, Deakin, Leicht, & Sealey, 2012) and torque production (Palmer & Sleivert, 2001) as a result of a particular strength training session.

7.3 Results

The C_R was significantly greater for the Post-RE test compared to the Base-RE test during stages 1 and 2 ($P < 0.05$) and significantly greater for the running session compared to the Base-RE test during stage 2 ($P < 0.05$; **Figure 7.2.**). The RPE was significantly greater for Post-RE test compared to Base-RE test ($P < 0.05$; **Figure 7.2.**) during stage 2 although TTE was significantly less during Post-RE (269 ± 69 sec) compared to Base-RE (331 ± 100 sec) ($P < 0.01$).

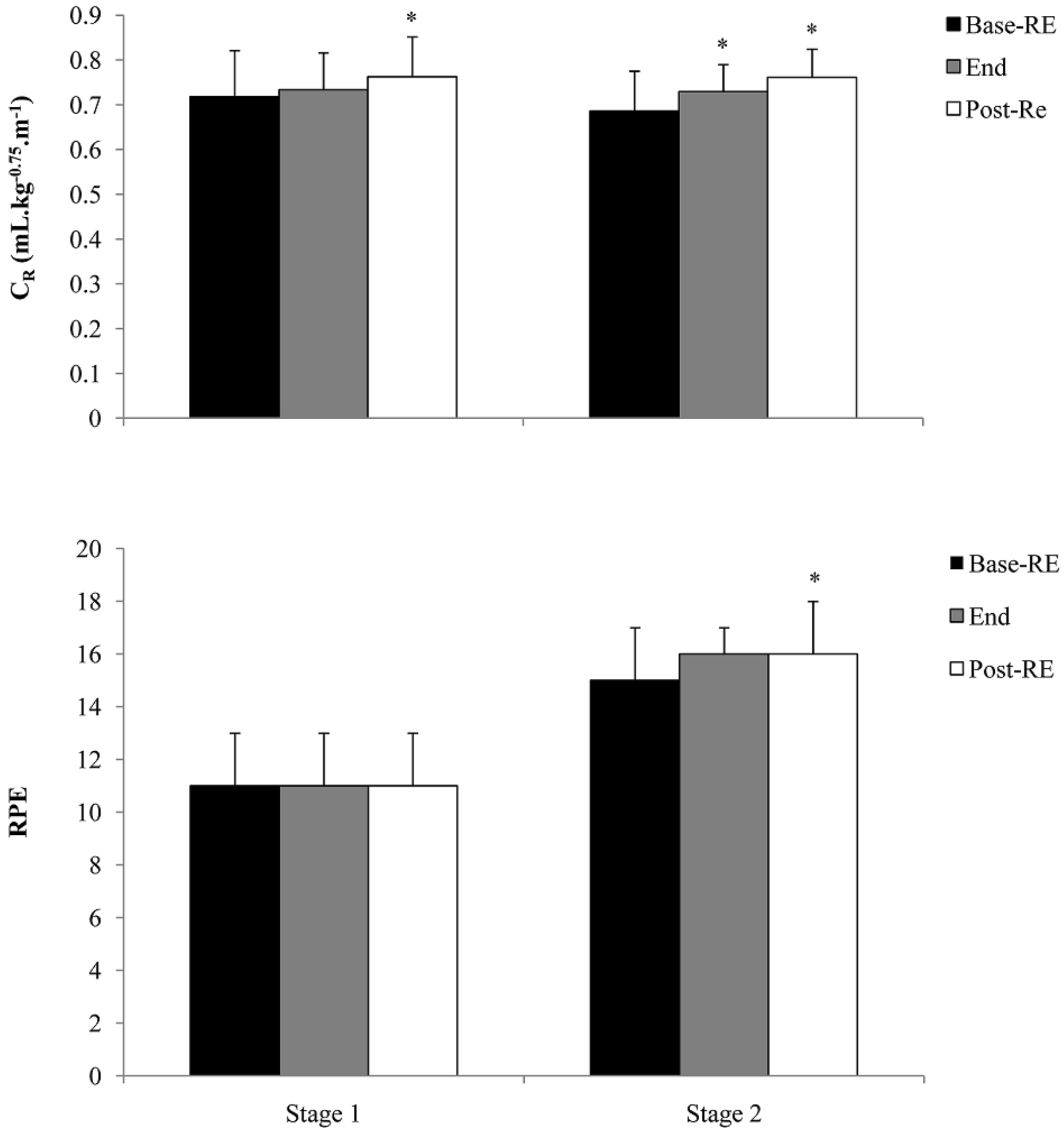

Figure 7.2. The oxygen cost of running (C_R) and rating of perceived exertion (RPE) during the stages 1 and 2 of the base running economy test (Base-RE), running session (End) and post running economy test (Post-RE)

* Significantly greater than the base running economy test ($P < 0.05$)

The H_{ROM} was significantly less for the running session and Post-RE test compared to Base-RE test ($P < 0.05$) during stages 1 and 2 (**Figure 7.3**). The KF_S for Post-RE test was significantly less than Base-RE test ($P < 0.05$) during stage 2. The torque was significantly reduced for all time points following strength training (**Figure 7.4**).

No significant relationships were found between the running performance variables (i.e. C_R, RPE and TTE), running kinematics and torque for the percentage differences between Base-RE, running session and Post-RE during Stages 1 (r = 0.12-0.41), 2 (r = 0.03-0.51) and TTE (r = 0.06-0.18) ($P \geq 0.05$).

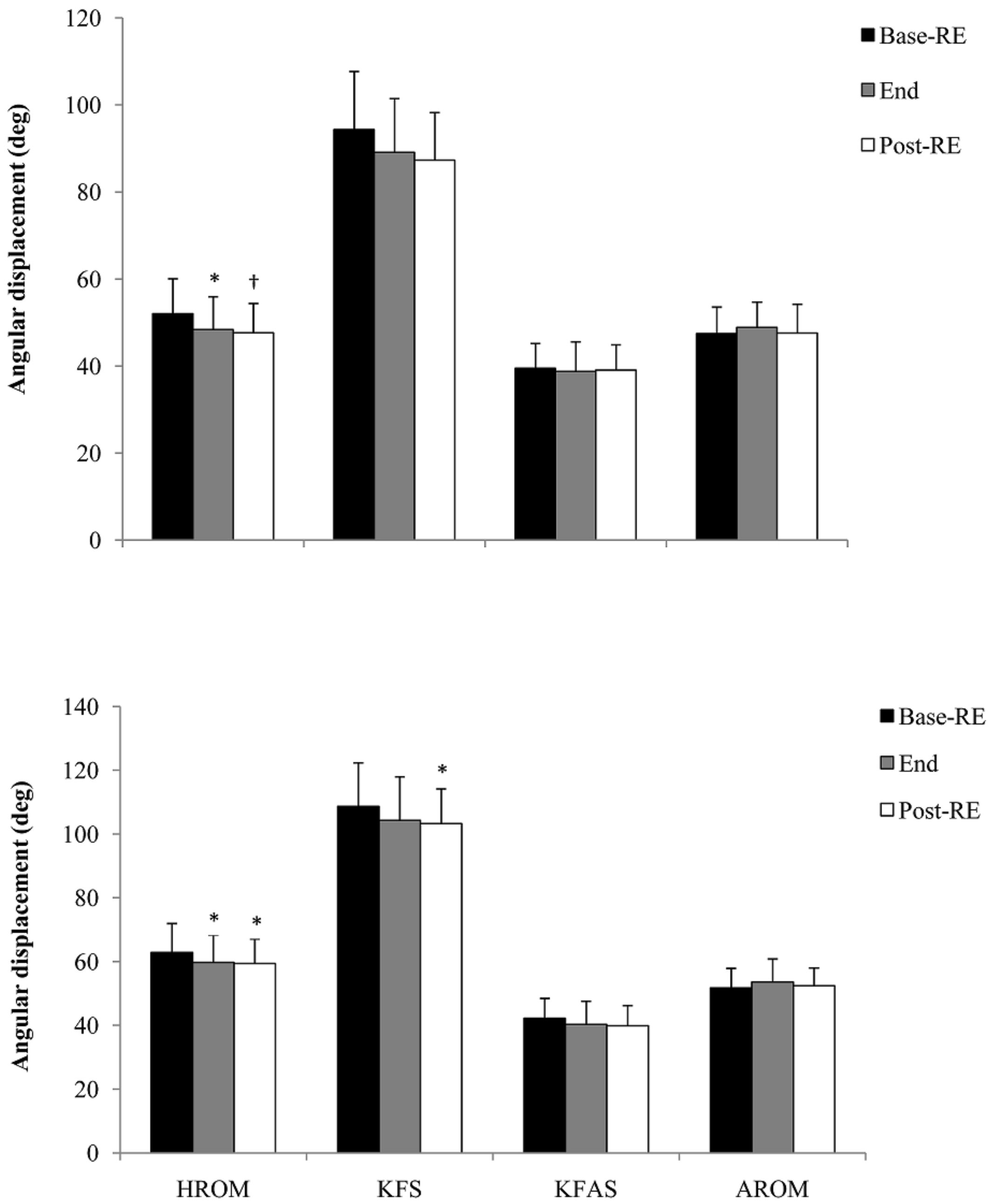

Figure 7.3. The angular displacements in degrees (deg) for hip range of motion (H_{ROM}), knee flexion during the swing phase (KF_S), knee flexion after foot strike (KF_{AS}) and ankle range of motion (A_{ROM}) during Stages 1 (top) and 2 (bottom) for the base running economy test (Base-RE), running session (End) and post running economy tests (Post-RE)

* Significantly less than the base running economy test ($P < 0.05$); † ($P < 0.01$)

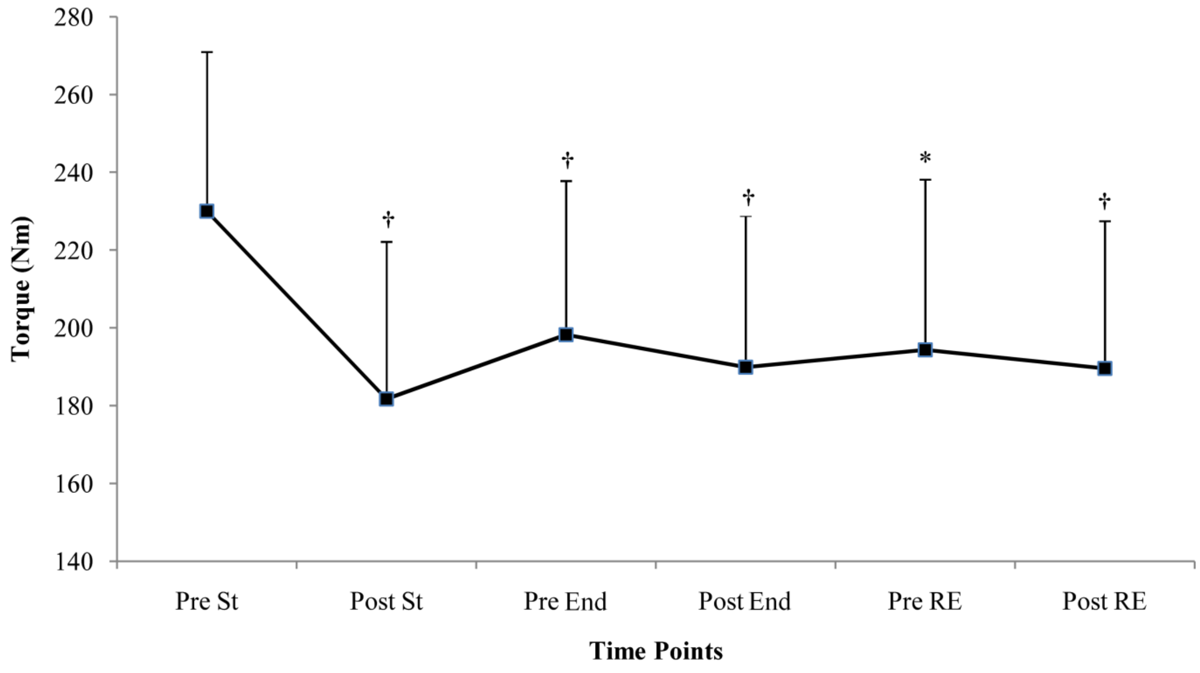

Figure 7.4. The torque production measure prior to– (Pre St) and following (Post St) the strength training session, prior to– (Pre End) and following (Post End) the running session and prior to– (Pre RE) and following (Post RE) the experimental running economy test

* Significantly less than Pre St ($P < 0.05$); † ($P < 0.01$)

7.4 Discussion

The results showed that strength training increased C_R and reduced H_{ROM} and torque 6 hours post. In addition, C_R increased and H_{ROM}, KF_S and torque decreased one day following strength and endurance training performed 6 hours apart. These findings support the hypothesis that running performance will be impaired 6 hours following strength training and that the combination of strength and endurance training performed on a single day will affect running performance the following day.

The increase in C_R during the running sessions is similar to a previous study that has shown an elevation in VO_2 during sub-maximal running 8 hours following strength training (Palmer and Sleivert, 2001). A recent study by Doma and Deakin (2012) reported no effect on RE 6 hours following strength training. However, the authors suggested that the deleterious effects of strength training on RE was limited since strength training exercises were performed with slow eccentric contractions (i.e. four seconds). Alterations in C_R may have been observed in the present study since the strength training exercises were performed at faster contraction velocities (i.e. self-paced). It has previously been reported that strength training with fast compared to slow contraction velocities caused greater exercise-induced fatigue (Ide et al., 2011). However, further research is warranted to systematically examine the effect of strength training contraction velocity on running performance.

The current study showed a significant reduction in H_{ROM} 6 hours following strength training and agrees with previous studies that have shown a compromise in lower extremity joint range of motion during running as a result of exercise-induced fatigue (Paschalis, et al., 2007; Reeves et al., 2003). The reduction in H_{ROM} following strength training in the present study may be due to increased muscle stiffness as there is evidence suggesting that exhaustive exercises alters the visco-elastic properties of the tendons and increases the stiffness of the joint, muscles and tendons (Reeves, et al., 2003). As a result, the reduction in joint range of motion may alter the length-tension relationship and impair neuromuscular performance of the lower extremity. In fact, Kellis and Liassou (2009) showed that localised muscle fatigue following isokinetic contractions caused changes in lower extremity kinematics in conjunction with increased muscle activation of the knee extensors and plantar flexors during toe-off and increased knee flexors during the swing phase. The increase in muscle activity suggests that muscles may use additional energy to compensate for alterations in running kinematics which would elevate the metabolic cost of running.

The findings from the present study showed further alterations in C_R and lower extremity running kinematics during Post-RE (i.e. one day following strength and endurance training) compared to the running session (i.e. 6 hours following strength training). The C_R during the Post-RE test was significantly greater at stages 1 and 2 whereas the C_R was significantly greater only at stage 2 during the running session. In addition, a significant increase in RPE was only found during the Post-RE test at stage 2. Furthermore, whereas H_{ROM} was the only kinematic parameter that was significantly less during the running session, both H_{ROM} and KF_S were significantly less during the Post-RE test. These findings demonstrate that strength and endurance training sessions performed in a single day, despite a 6 hour recovery period, generates an accumulation effect of fatigue on running performance the following day. Whilst TTE was not collected during the running session as it was treated as an endurance training session, TTE was significantly reduced during Post-RE which exemplifies that concurrent strength and endurance training also impairs running performance at maximal effort the following day.

Whilst previous studies have found that sub-maximal endurance sessions may accelerate recovery (Faude, et al., 2009; Fujita, et al., 2009), the current study showed an increase in C_R during Post-RE the following day. Such findings suggest that the running session performed in conjunction with strength training may have induced an additional stimulus of fatigue as opposed to facilitating recovery the following day. Drummond et al (2005) examined strength and endurance training sequence on EPOC. The authors showed that EPOC was greatest when strength training preceded endurance training compared to strength training alone, endurance training alone or when endurance preceded strength training. These findings indicate that a combination of strength and endurance training elevates metabolic cost and that strength training may be the primary contributor to the accumulation effect of the two modes of training. Given the nature of the current findings, it would be interesting to systematically examine the effect of sequence of strength and endurance training on running performance the following day.

Whilst the present findings showed an increase in C_R with a concomitant reduction in MFGC 6 hours following strength training, there was no relationship between the percentage differences in MFGC and RE. These results are similar to findings by Chen and colleagues (2009) where RE was impaired for only two days following downhill running yet MFGC was reduced for five days. The lack of relationship between RE and MFGC suggests that the compromise in RE may not only be governed by MFGC. This is not surprising given that attenuation in RE following strenuous exercises has been associated with muscle soreness, muscle damage, increased level of perceived exertion and alterations in running kinematics (Chen, et al., 2009; Paschalis, et al., 2007). Thus, the mechanisms responsible for a decrement in RE appear to be a complex phenomenon involving various physiological and physical measures. Nonetheless, given that C_R was increased with a concomitant reduction in torque, MFGC may in part have contributed to alterations in C_R following strength training in the present study.

No significant relationships were found between changes in lower extremity kinematics, MVC and running performance variables (i.e. C_R, RPE and TTE) from the current results. These findings are in agreement with Collins et al (2000) who reported no significant relationship between RE and lower extremity running kinematics following high intensity interval training. The lack of relationship between running performance variables and running kinematics could account for differences in coping strategies given that the training background varied between the participants in the present study. Studies have found significant day-to-day variability in step length within individuals (Morgan, Martin, Krahenbuhl, & Baldini, 1991). It has also been shown that variability and fluctuation in running gait cycle were greater for non-runners compared to experienced runners, demonstrating that spatiotemporal organisation during running differs between individuals with varying running experiences. Subsequently, whilst a relationship was not found between running kinematics and the running performance variables, given that significant differences were found in both performance measures following strength and endurance training, it is reasonable to assume that changes in running technique may in part have contributed to an increase in C_R in the current study. However, this speculation warrants further investigation by incorporating a more homogenous group of runners.

7.5 Conclusion

This study showed that strength training elevates C_R, decreases MFGC and reduces lower extremity joint range of motion with 6 hours of recovery. Additionally, performing strength and endurance training on the same day appears to intensify the effects of strength training on running performance the following day compared to strength training alone. Whilst studies have shown that strength training does not affect RE despite EIMD with a 24 hour recovery period (Marcora and Bosio, 2007; Paschalis, et al., 2007), the current findings indicate that strength training may cause detrimental effects on sub-maximal and maximal running performance 24 hours post when combined with a moderate to high intensity endurance training session.

7.6 Practical application

According to the current findings, high intensity strength training impaired RE 6 hours post and impaired RE and TTE 18 hours following strength and endurance training sessions performed on the same day 6 hours apart. Subsequently, moderate to high intensity running sessions should not be performed within the hours following high intensity strength training as prescribed in the current study amongst moderately trained to trained endurance athletes with minimal strength training experience or those that are detrained from strength training. When incorporating high intensity strength and endurance training into a concurrent training program, the two modes of training sessions should be prescribed on alternating days in order to ensure recovery between each mode of training.

Chapter 8

The effects of strength training and endurance training order on running -economy and -performance

The study in Chapter 7 showed that a strength training session that consisted of multiple lower extremity strength training exercises performed at a self-selected pace impaired RE and MVC and altered running kinematics 6 hours post. It was also found that the combination of strength and endurance training performed on the same day continued to impair RE and altered running kinematics the following day. These findings suggest an accumulation effect of fatigue from one mode of training session to the next. However, it was unknown whether the combination of strength and endurance training impaired running performance due to strength training sessions being prescribed prior to endurance training sessions. Subsequently, this study (Chapter 8) examined the effects of altering the sequence of strength and endurance training on the same day and their impact on running performance the following day. The findings from this study will assist in determining the contribution of each mode of training to the accumulation effect of fatigue when strength and endurance training sessions are combined on the same day.

Doma, K., & Deakin, G.B. (2013). The acute sequence effect of strength and endurance training on running performance. *Applied Physiology, Nutrition and Metabolism,* In Press.

8.1 Introduction

Incorporating both strength and endurance training sessions in the one training program, known as concurrent training (Hickson, 1980), is common due to its convenience. However, studies have shown that concurrent training can induce sub-optimal strength and/or endurance adaptations (Gergley, 2009; Glowacki, et al., 2004). Several mechanisms have been proposed to explain the interference of strength development, including alterations of neural recruitment (Dudley & Djamil, 1985), fibre-type transformation (Dudley & Fleck, 1987) and disturbance of protein synthesis (Rennie & Tipton, 2000). However, factors attributing to sub-optimal endurance adaptation as a result of concurrent training have received little attention.

Given that strength training has been shown to impair muscle force generation capacity from 24-48 hours post training (Häkkinen, et al., 1988), strength training may interfere with the quality of subsequent endurance training sessions. Indeed, studies have shown that strength training impaired RE, running TTE and running TTP 8– (Palmer et al., 2001), 6– (Doma & Deakin, 2012) and 24 hours (Marcora and Bosio, 2007) post training. Subsequently, strength training may cause difficulty in optimising endurance adaptation if performances during endurance training sessions are repeatedly interfered over the course of a concurrent training program.

Chtara and colleagues (2005) examined the effect of strength and endurance training sequence on endurance adaptation following a 12-week concurrent training program. The results showed that the improvement in 4 km running time-trial performance was greater for the ES group compared to the SE group. The authors suggested that residual fatigue resulting from strength training may have affected the quality of following endurance sessions and therefore attenuated optimal training stimuli for endurance adaptation. Whilst these findings indicate that endurance adaptation may be influenced by the timing in which modes of exercises are prescribed, the acute effects of strength and endurance training sequence on running performance was not examined.

A study conducted by Deakin (2004) investigated the acute sequence effect of strength and endurance training on sub-maximal cycling performance. In this study, strength and endurance exercises were performed three hours apart in randomised order with a sub-maximal cycling performance test conducted three hours following the last training session of each exercise sequence. The results showed that the physiological cost of cycling was greater three hours following the sequence of strength-endurance training compared to the sequence of endurance-strength training. These findings suggest that the strength-endurance sequence may have generated cumulative effects of fatigue. However, Deakin (2004) examined training sequence on endurance performance on the same day. Furthermore, the recovery period between strength and endurance training was only 3 hours with endurance performance measures limited to physiological cost of cycling prescribed at a single intensity on the same day. It is unknown whether the sequence of strength and endurance training sessions would have an impact on subsequent endurance performance the following day when the recovery period between each mode of training session is greater than 3 hours. Such investigation would better represent a typical concurrent training day where one mode of training session is performed in the morning and the other in the afternoon. Furthermore, examining the sequence of strength and endurance training sessions the following day will shed light on the inter-day fatigue and recovery dynamics of a typically prescribed concurrent training program.

To date, the investigation of strength and endurance training sequence, separated by 6 hours, on sub-maximal (i.e. RE) and maximal (i.e. TTE) running performance the following day has not been conducted as far as the authors are aware. Furthermore, the impact of strength and endurance training sequence on running kinematics has not been examined. Determining the sequence effect of training on running performance the following day may shed light on the recovery dynamics during daily concurrent training sessions.

The purpose of the current investigation was to systematically examine the acute effects of strength and endurance training sequence on RE, running TTE and lower extremity running kinematics the following day. It was hypothesized that running performance will be impaired to a greater degree the following day when strength training precedes endurance training as opposed to endurance training followed by strength training.

8.2 Methods

Participants

Fourteen trained and moderately trained runners (mean ± standard deviation: age 23.3 ± 6.1 years; height 1.8 ± 0.1 m; body mass 74.6 ± 8.0 kg; VO_{2max} 62.0 ± 6.0 $mL.kg^{-1}.min^{-1}$) took part in the study. The trained runners were middle to long distance runners (1500-10,000 m) had all run a 10,000 m time trial faster than 37 minutes during the last 6 months. The moderately endurance trained runners were undertaking moderate three to four high intensity endurance training sessions and had various sporting backgrounds during the last 6 months. The participants did not undertake any lower extremity strength training exercises for at least 2 months prior to the study.). The participants did not have experience in strength training or have not undertaken high intensity strength training for the past 6 months. Each participant completed informed consent before taking part in any testing procedures which were approved by the Institutional Human Research Ethics Committee and were run in accordance with the Declaration of Helsinki.

Research design

The study was conducted across five weeks with the first week consisting of a familiarisation session and VO_{2max} test. The familiarisation session allowed participants to familiarise themselves with the protocols and equipment and to carry out a 6RM assessment. The VO_{2max} test was a continuous incremental protocol that has been used previously (Doma, Deakin, & Sealey, 2012). The 6RM assessments were conducted as described previously (Baechle & Earle, 2008) for incline leg press (Maxim MF701, Australia), leg extension and leg curls (Avanti, B253 Olympic Bench, Australia). During the second week, the participants undertook two RE tests that were separated by at least two days for familiarisation purposes as well as to provide a baseline for comparisons. The data collected during the second RE test was used as Base-RE. During the third week, two strength sessions were conducted as a washout period to standardise possible early on-set of neuromuscular adaptations, since the use of the repeated bout effect (via the use of a second strength training session) has been shown to reduce the negative influence of a single strength training session on running performance (Burt, Lamb, Nicholas & Twist, 2013). During the fourth and fifth week, participants undertook a running session 6 hours following a strength session (SR sequence) and a strength session 6 hours following a running session (RS sequence) in randomised order with 7 days of recovery in-between the two sequences (**Figure 8.1**). A RE test was conducted 24 hours following the strength session for the SR sequence (SR-RE) and 24 hours follow the running session for the RS sequence (RS-RE). The running sessions that were performed either prior to or following the strength sessions were treated as endurance training sessions which were separate from the RE tests and were used to examine the acute sequence effect of strength and endurance (i.e. running session) training on running performance (i.e. RE test). Maximal voluntary contraction tests were conducted prior to and following the strength sessions, running sessions and RE tests for the SR– and RS sequences. Technical and biological variations were controlled by calibrating all measurement equipment, requiring participants to maintain their training intensity and volume during the course of the study, conducting the RE tests at the same time of day, participants wearing the same shoes for every test, refraining from high intensity physical activity for at least 24 hours prior to testing and refraining from caffeine– and food intake for at least 2 hours prior to testing.

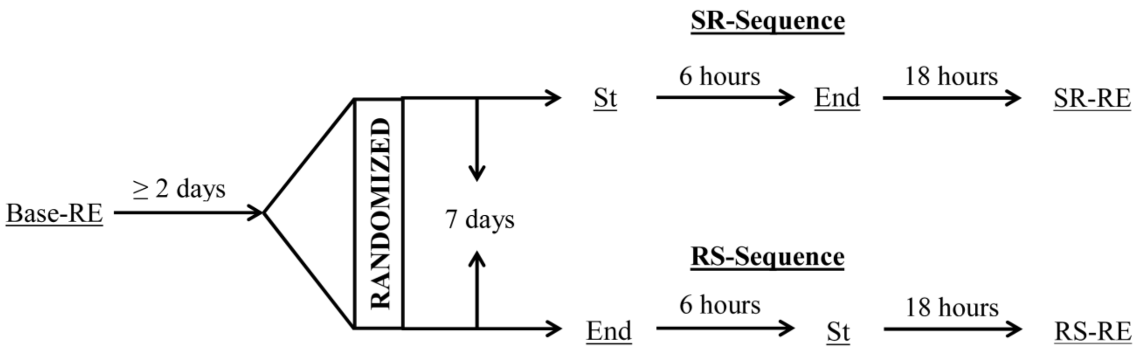

Figure 8.1. Schematic diagram demonstrating the progression of the sessions from the baseline running economy test (Base-RE), the strength session (St) and running session (End) and the running economy tests during the strength-running sequence (SR-RE) and running-strength sequence (RS-RE)

Strength session

The exercises were performed in the order of incline leg press with 6 sets of 6 repetitions and leg extension and leg curls with four sets of 6 repetitions for each exercise. The exercises were performed in an order to replicate a common procedure during strength training sessions where larger muscle groups are exercised first. A three minute recovery period was provided between each set and between each of the strength training exercises.

Running session

Prior to the running session, a progressive warm-up was conducted on the treadmill walking at 5 km.hr^{-1} and then jogging at 8–, 10– and 12 km.hr^{-1} for one minute, respectively. The running session was a three stage discontinuous incremental protocol which was conducted on a treadmill and was similar to the RE test with the first two stages set at 70– and 90% of VT_2 for 10 minutes. However, the last stage consisted of intervals with work to rest ratios of approximately 1:1 at 110% of VT_2 (**Figure 8.2.**). Specifically, there were four intervals with a rest period of 1.5 minutes between the first, second and third interval and two minutes of rest between the third and fourth interval. There were also two minutes of rest between the three incremental stages.

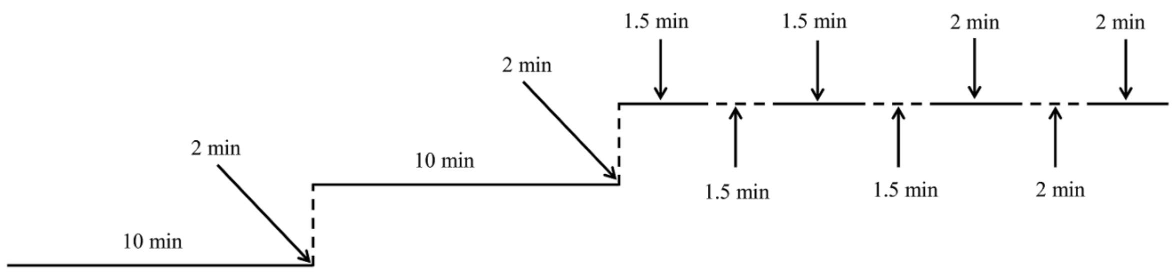

Figure 8.2. A schematic demonstrating the protocol of the running session with solid and dashed lines denoting running and rest, respectively

Running economy test

The RE tests were conducted following a warm-up identical to that of the running session. The RE protocols consisted of three incremental stages running at 70–, 90– and 110% of the VT_2, respectively (Doma, Deakin, & Sealey, 2012). The participants ran for 10 minutes during the first two stages and then to exhaustion during the last stage to determine TTE. There were two minutes of passive rest between each stage. The VT_2 for each participant was determined from the VO_{2max} test by ascertaining the inflection point of VE with respect to

CO_2 on a scatter diagram (Neder et al. 2006). The VT_2 was used due to its high reliability (Neder et al. 2006). The C_R was used to indicate RE where VO_2 is expressed in millilitres per kilogram to the power of 0.75 per metre ($mL.kg^{-0.75}.m^{-1}$). This particular expression for C_R was selected as it has been reported to minimize between-participant variability (Doma, Deakin, Leicht, & Sealey, 2012). The C_R was averaged during the last 5 minutes of the first two stages to ensure that the participants reached steady-state running, which was defined as < 10% change in VO_2 per minute (Reeves et al. 2004). Values for RPE were also collected on the 9th minute of the first two stages and every minute during the last stage (i.e. TTE). The RPE of the middle time points during the shortest TTE of a given RE test was used for comparisons (e.g. if the TTE for a given participant was 5 minutes for SR-RE, then the RPE for the third minute of SR-RE was compared with the third minute of Base-RE and RS-RE). The RPE collected during the three stages are expressed as RPE 1, RPE 2 and RPE 3, respectively, for the subsequent sections of the paper.

Kinematic Analyses

Running gait was captured at 9 minutes 30 seconds of the first two stages of the Base-RE, SR-RE and RS-RE tests. At least 10 strides of kinematic data were recorded for each motion capture at 100 Hz using a 3-D 8-camera optical motion analysis system (VICON Motion Systems, Oxford, UK). Static calibrations for the optical cameras were completed for each testing session and ensured an image error of < 0.15 pixels. The measuring volume covered 1.5 m x 3 m x 2 m (width, length, height). Body segments that were captured included the pelvis, thighs, shank and the feet using 16 retro-reflective markers (14 mm diameter) that were placed by a single well trained investigator (Nexus Plug-in Gait Model, Oxford, UK). Running gait parameters included A_{ROM}, KF_S, KF_{AS} and H_{ROM} in the sagittal plane. Raw kinematic data were filtered using Woltring filtering routing. The MSE was set to 20 mm^2 in accordance with a detailed residual analysis (Winter 2008). Kinematic analysis during the last stage was not conducted due to its lesser reliability compared to the first two stages (Doma, Deakin, & Sealey, 2012).

Maximal voluntary contraction test

A custom-built dynamometer chair (James Cook University, Australia) was used to conduct the maximal isometric contractions of the knee extensor muscles. There were three contractions with each contraction held for 6 seconds and 1.5 minutes rest between each contraction (Doma & Deakin, 2012). Torque was measured by positioning the knee joint at 110° with a force transducer secured superior to the medial and lateral malleoli. The dynamometer chair was calibrated by placing a known weight on the force transducer. Torque was calculated by averaging the values over the 6-second contraction with the largest torque being reported amongst the three contractions.

Sample size

Following a pilot study on the reliability of the RE test and MVC test used in the current study, the within-participant CV for C_R, RPE, TTE and torque production amongst trained and moderately endurance trained men (n = 14) showed within-participant CV's of 2.5–, 3.6–, 9.2– and 8.3%, respectively (Doma, Deakin, Leicht, & Sealey, 2012). According to a nomogram for the estimation of measurement error with the use of CV (statistical power of 90%) (Atkinson et al. 2006), the percentage WD for the current sample size (n = 14) for C_R, RPE, TTE and torque production were found to be 3–, 4.5–, 11– and 10%, respectively. These percentage differences are smaller than previous reports that have shown significant differences in the oxygen cost of running (Palmer et al. 2001), RPE (Doherty et al. 2004), TTE (Esposito, Ce, & Limonta, 2012) and torque production (Palmer et al. 2001) as a result of a particular intervention.

Statistical analysis

The measure of centrality and spread for all data are expressed as mean ± standard deviation. A one-way ANOVA with one between participant factor, exercise order, was used to determine differences in C_R, RPE and TTE between Base-RE, SR-RE and RS-RE. A two-way ANOVA (time x sequence) with one between participant factor, exercise order, was then used to determine differences in torque production for within and between the SR– and RS sequences. Post hoc tests with Bonferroni's pairwise adjustments were then used to locate the difference. The alpha level was set at 0.05. All data were analysed using the Statistical Package for Social Sciences (SPSS, version 18, Chicago, IL).

8.3 Results

The C_R was significantly greater for SR-RE (0.76 ± 0.10- and 0.77 ± 0.07mL.kg$^{-0.75}$.m^{-1}) compared to Base-RE (0.72 ± 0.10- and 0.70 ± 0.11 mL.kg$^{-0.75}$.m^{-1}) and RS-RE (0.73 ± 0.09- and 0.72 ± 0.09 mL.kg$^{-0.75}$.m^{-1}) during stages 1 (*P* = 0.013, 0.047) and 2 (*P* = 0.014, 0.022) although no differences were found during stage 3 (P = 0.73) (**Figure 8.3.**). The RPE 2 and RPE 3 were significantly greater for SR-RE compared to Base-RE (P = 0.002, 0.003) and

RPE 2 and RPE 3 were significantly greater for RS-RE compared to Base-RE (P = 0.017, 0.030) (**Figure 8.4.**). The TTE was significantly less during SR-RE (237.8 ± 67.4sec) and RS-RE (275.3 ± 68.0sec) compared to Base-RE (335.4 ± 92.1sec) (P = 0.003, 0.008) (**Figure 8.5.**). The H_{ROM} was significantly less for SR-RE compared to Base-RE during stages 1 and 2 (P = 0.044, 0.019) and KF_S was significantly less for SR-RE compared to Base-RE during stage 2 (P = 0.026) (**Figure 8.6.**).

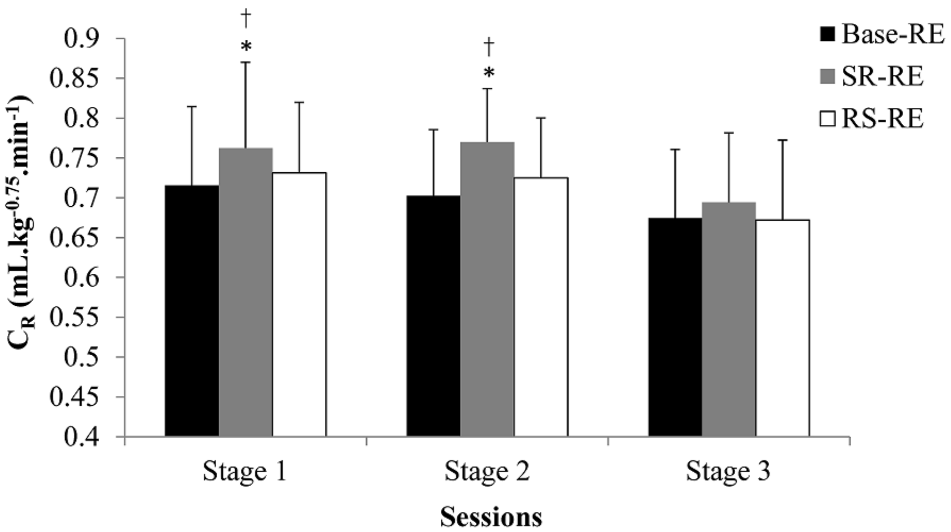

Figure 8.3. The cost of running (C_R) for baseline running economy (Base-RE), running economy for the strength-running sequence (SR-RE) and running economy for the running-strength sequence (RS-RE) during Stages 1, 2 and 3

* Significantly greater than Base-RE (P < 0.05)

† Significantly greater than RS-RE (P < 0.05)

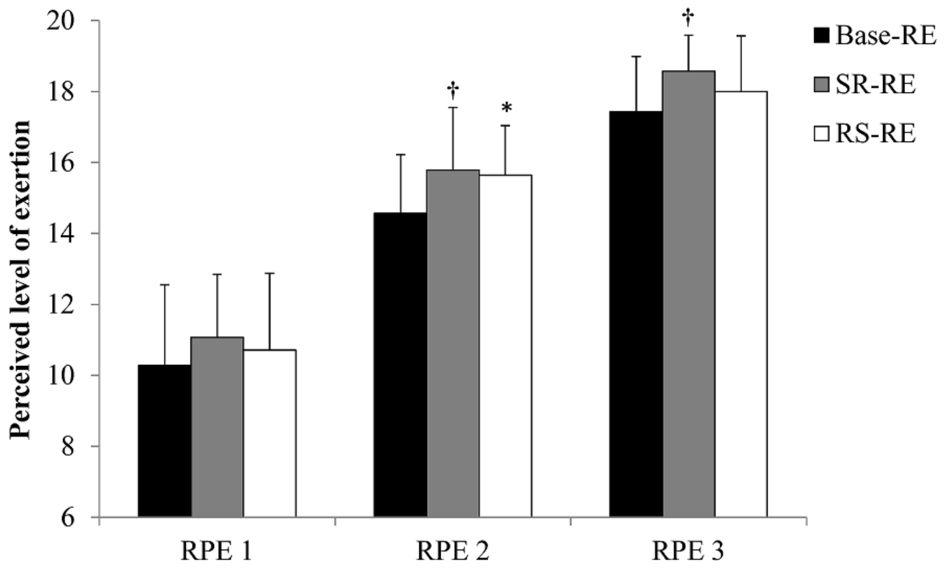

Figure 8.4. The rating of perceived exertion (RPE) for the baseline running economy (Base-RE), running economy for the strength-running sequence (SR-RE) and for the running-strength sequence (RS-RE) during Stages 1 (RPE 1), 2 (RPE 2) and 3 (RPE 3)

* Significantly greater than Base-RE ($P < 0.05$); † ($P < 0.01$)

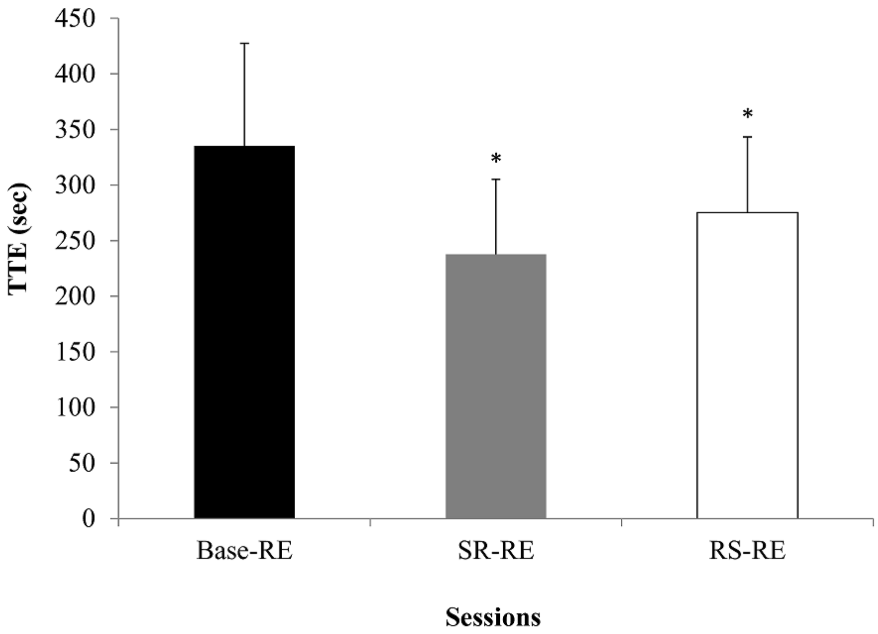

Figure 8.5. The time-to-exhaustion (TTE) recorded for the baseline running economy (Base-RE), running economy for the strength-running sequence (SR-RE) and running economy for the running-strength sequence (RS-RE)

* Significantly less than Base-RE ($P < 0.01$)

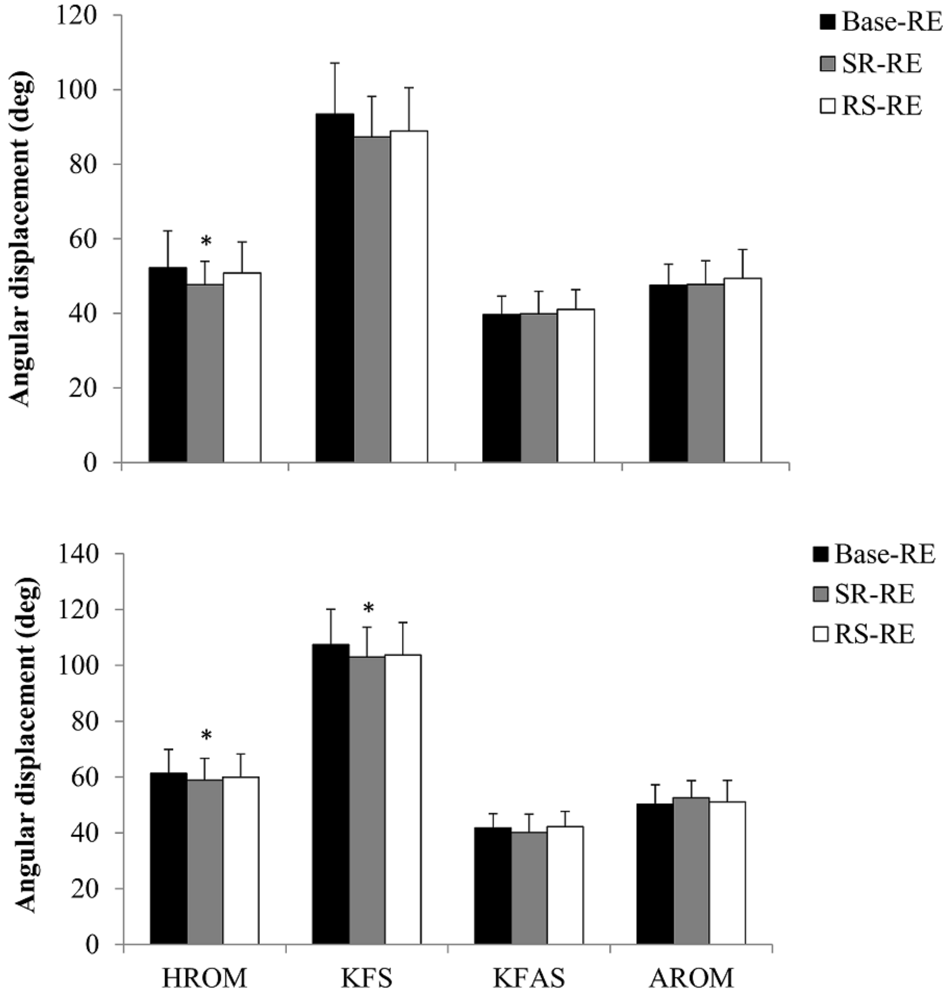

Figure 8.6. The angular displacements of the hip range of motion (H_{ROM}), knee flexion during swing phase (KF_S), knee flexion after foot strike (KF_{AS}) and ankle range of motion (A_{ROM}) for the baseline running economy test (Base-RE) and running economy tests for the strength-running sequence (SR-RE) and the running-strength sequence (RS-RE) during Stages 1 and 2

* Significantly less than Base-RE ($P < 0.05$)

For the torque production, there was a significant effect of time (P = 0.001), however, no significant interaction effect was found for sequence ($P \geq 0.05$) (**Figure 8.7.**). Post hoc comparison showed that torque was significantly reduced for every 5 time points measured following the strength training session during the SR-sequence (P = 0.001). For the RS sequence, no differences were found following the running session ($P \geq 0.05$) although significantly reduced for the three time points measured following the strength training session (P = 0.003, 0.002, 0.001). No significant differences were found for the other performance variables between the RE tests and between the other time points for torque ($P \geq$ 0.05). Regarding cross randomization, no effect of exercise order was found for any of the variables measured ($P \geq 0.05$).

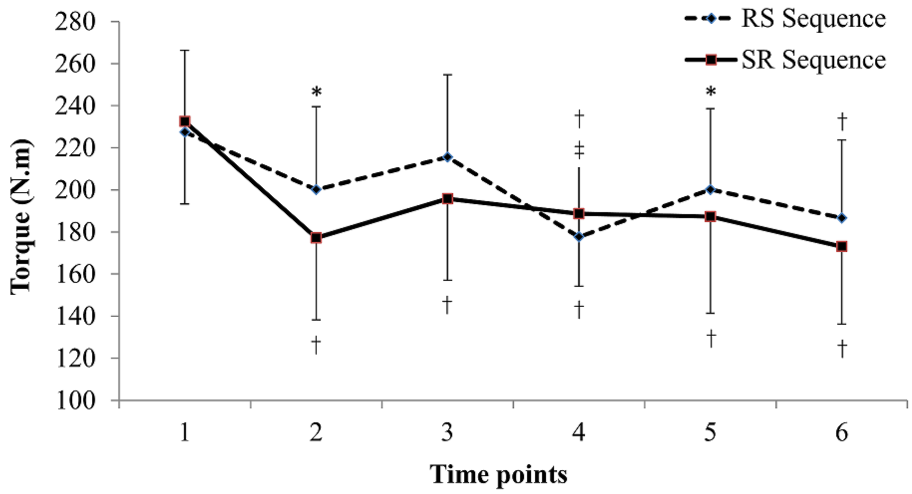

Figure 8.7. The torque production at time points prior to– (1) and following (2) the strength training, prior to– (3) and following (4) the endurance training session and prior to– (5) and following (6) the running economy test for the SR sequence and prior to– (1) and following (2) the endurance training session, prior to– (3) and following (4) the strength training session and prior to– (5) and following (6) the running economy test for the RS sequence

* Significantly less than time point 1 ($P < 0.05$); † ($P < 0.01$)

‡ Significantly less than time point 3 ($P < 0.01$)

8.4 Discussion

The current study showed that C_R was significantly greater and H_{ROM} and KF_S was significantly less during SR-RE compared to Base-RE. However, TTE was significantly less and RPE was significantly greater during both SR-RE and RS-RE compared to Base-RE. These findings support the hypothesis that strength training before endurance training will impair running performance the following day to a greater degree compared to endurance training before strength training.

The significant increase in C_R during SR-RE with no differences found during RS-RE compared to Base-RE demonstrates that strength and endurance training sequence had an effect on running performance the following day. Whilst Deakin (2004) examined strength and endurance training sequence on cycling performance on the same day, it was reported that the physiological cost of sub-maximal cycling was greater three hours following strength-cycling compared to cycling-strength sequences. In light of the findings from the current study and that by Deakin (2004), strength training may be the primary mode of exercise contributing to the accumulation effect of fatigue responsible for impaired endurance performance. Previous reports have shown that the physiological cost of sub-maximal running (Palmer et al. 2001) and cycling (Deakin 2004) increased 8– and 3 hours following strength training, respectively.

It has been reported that venous blood oxygen saturation reduces during isometric contraction of the forearm (Barcroft, Greenwood, & Whelan, 1963) suggesting that oxygen extraction increases with sustained muscle contraction. Further, Yamada and colleagues (2008) showed a significant relationship between reduction in muscle activity and changes in muscle oxygenation during sub-maximal isometric contractions. From these previous findings, it is assumable that C_R in the current study may have increased due to greater oxygen extraction from the muscles of the lower extremity compared to running in a non-fatigued state. Furthermore, changes in oxygen metabolism may have occurred due to inefficient neural recruitment patterns as indicated by alterations in lower extremity kinematics due to pre-existent local muscle fatigue from previous strength and endurance training sessions.

Given that a 6-hour recovery period was incorporated between strength and endurance training in the current study, the endurance training session may have been performed in a pre-exhausted state due to residual fatigue from the preceding strength training session. This is supported by the significant reduction in MVC prior to the running session during the SR-sequence. However, MVC returned to baseline values 6 hours following the running session during the RS-sequence suggesting that possible residual effects of fatigue generated from the running sessions may have been eliminated prior to the strength training session. Consequently, an accumulation effect of fatigue appears not to have occurred during the RS-sequence over the two day testing period. Indeed, studies have reported that strength training reduces MVC from 24-48 hours and this has been attributed to depletion of muscle glycogen (Green 1990), muscle –soreness and –damage (Skurvydas et al. 2010). Alternatively, it has been shown that MVC is not affected 24 hours following 60 minutes of moderate to high intensity endurance training (Bentley et al. 2000). Subsequently, endurance training performed following strength training may augment the physiological responses induced by strength training (e.g. muscle glycogen depletion, muscle soreness and muscle damage) and thereby attenuating RE the following day.

The TTE was significantly reduced for both SR-RE and RS-RE demonstrating that running at maximum effort is impaired the day following strength and endurance training regardless of the sequence of the mode of training. However, no differences were found in C_R during stage

3 between Base-RE, SR-RE and RS-RE. These findings indicate that the participants' physiological state was similar at exhaustion despite differences in TTE. Subsequently, the rate of increase in fatigue may have been greater during SR-RE and RS-RE compared to Base-RE and therefore contributed to terminating their running earlier. Interestingly, the difference in TTE between SR-RE and RS-RE was 10%, which is in proximity to the worthwhile differences (i.e. 11%) for TTE determined for the RE protocol with the current sample size (n = 14). In addition, RPE 3 was significantly greater during SR-RE although no significant differences were found in RPE for this particular time point during TTE. As a result, the subjects in the current study appeared to perceive running to be harder mid-way through TTE during SR-RE compared to RS-RE indicating a sequence effect above VT_2.

Whilst reduction in MVC may have attributed to an increase in C_R during SR-RE in the present study, no significant relationship was found between the percentage differences in C_R and MVC for the SR- and RS-sequences. These findings confirm the study conducted by Chen et al (2007) where MVC remained reduced for 5 days following downhill running although RE was impaired for only two days. Palmer et al (2001) also found no effect on MVC 8 hours following strength training yet RE was impaired. This lack of relationship between MVC and C_R would be expected as reports have shown that RE was impaired following strenuous exercises with an increase in muscle –soreness and –damage (Chen et al. 2007), elevation in level of perceived exertion and alterations in running kinematics (Bonacci et al. 2010). Subsequently, the physiological process contributing to the decrement in RE appears to be complex involving various mechanisms. In addition, running is performed dynamically requiring multiple muscle groups to contract repetitively in short bursts whilst performing various contraction types (e.g. concentric-, eccentric- and isometric contractions). Thus, it is difficult to directly relate running performance measures to a single 6-second isometric contraction of one muscle group. Nonetheless, given that the effect of strength and endurance training sequence was similar between C_R and MVC, the impaired properties of the muscle may in part have contributed to an increase in C_R in the present study.

In addition to an increase in C_R, significant reductions were found in H_{ROM} and KF_S during SR-RE although no significant differences were found in the selected kinematic parameters during RS-RE, suggesting that the sequence effect of strength and endurance training was also present in running kinematics. The current study is the first to examine the effect of strength and endurance training sequence on running gait patterns as far as the authors are aware. Subsequently, directly comparing the kinematic results from the current study to literature is at present difficult. However, given that MVC was consistently reduced during the SR-sequence, neuromuscular fatigue may have caused inefficient motor unit recruitment patterns thereby altering running kinematics. Various studies have shown reductions in lower extremity joint range of motion during running as a result of neuromuscular fatigue following resistive-type exercises (Chen et al. 2007; Paschalis et al. 2007). It has been postulated that lower extremity range of motion may be compromised due to delayed onset of muscle soreness, inefficient neural recruitment patterns and decreased ability to use the stretch-shortening cycle (Chen et al. 2007; Braun et al. 2003). The reduction in KF_S in the current study may have caused an increase in hip flexor torque due to greater moment of inertia. These biomechanical modifications reduces efficiency of movement requiring greater energy expenditure for running. Subsequently, alterations in running kinematics may have contributed to increased C_R during SR-RE in the current study.

In summary, strength training performed prior to endurance training causes greater attenuation in running performance than endurance performed prior to strength training the following day. This sequence effect was also evident for altertions in lower extremity running kinematics. This phenomenon may occur due to endurance exercises augmenting the duration of fatigue generated by preceding strength training sessions.

The current study showed that the SR-sequence increased C_R with a concomitant reduction in MVC and alterations in running kinematics. The increase in the physiological cost of running as a result of performing strength and endurance training would hinder performance during a running session and impair optimum stimulus for training adaptation. From a practical view, running sessions at sub-maximal intensities should be performed the day after the RS-sequence as opposed to the SR-sequence. However, given that TTE was significantly less during both SR-RE and RS-RE, a recovery period of more than one day may be required following strength and endurance training regardless of the sequence of the mode of training when performing a high intensity running session. Whilst the current study demonstrated the sequence effect of strength and endurance training on running performance the following day, future research could examine this phenomenon over multiple days (e.g. 48- and 72- hours post) to enhance the understanding of fatigue and recovery dynamics as a result of concurrently training each mode of training session.

Chapter 9

The acute effect of concurrent training on running performance over 6 days

Chapter 8 showed that when strength training was performed 6 hours prior to endurance training as opposed to the opposite sequence, RE and MVC were impaired and running kinematics were altered to a greater degree the following day. These findings suggest that a sequence effect is evident when performing strength and endurance training sessions on the same day. Whilst these findings provide practical significance regarding prescription of training sequence, it was still unknown whether the accumulation effect of fatigue would be present, or worsen, when strength training was prescribed prior to endurance training over multiple days. Subsequently, this final study (i.e. Chapter 9) examined the effects of alternating-day strength training and consecutive-day endurance training on running performance over a 6-day period.

Doma, K., & Deakin, G.B. (2012). The acute effect of concurrent training on running performance over 6 days. Currently under review.

9.1 Introduction

The incorporation of strength and endurance training sessions in the one training program is known as concurrent training (Hickson 1980). Numerous studies have shown that concurrent training induces sub-optimal strength (Bell et al. 2000; Chtara et al. 2008; Dolezal et al. 1998) and endurance adaptations (Chtara et al. 2005; Gravelle et al. 2000; Nelson et al. 1990). The interference in strength development has been attributed to the physiological responses being antagonistic between each mode of training, known as the “chronic hypothesis” (Leveritt et al., 1999). Furthermore, the “acute hypothesis” contends that residual effects of fatigue generated by endurance training may impair muscular contractility essential for optimal strength adaptation (Leveritt et al., 1999). However, the mechanisms associated with interference of endurance adaptation have received little attention.

Chtara et al (2005) examined the effects of altering strength and endurance training sequence on endurance adaptation over 12 weeks and found that the improvement in running time-trial performance was less for the SE group compared to the ES group. The authors postulated that fatigue generated from strength training may have impaired the quality of the following endurance training sessions. Consequently, the acute hypothesis explaining the interference of strength adaptation may be similar to mechanisms responsible of sub-optimal endurance development. However, the study by Chtara and colleagues (2005) was limited to the chronic responses of concurrent training over 12 weeks. To date, little is known of the impact that strength training may have on the quality of subsequent endurance training sessions. This could be confirmed by investigating the acute effects of strength training on endurance performance.

Palmer et al (2001) reported that RE was impaired 8 hours following strength training although RE was unaffected 24 hours post. Similarly, Scott et al (2003) showed that strength training did not affect RE with a 24 hour recovery period, indicating minimal effect of strength training on sub-maximal running performance. However, it has been shown that strength training impaired running sprint ability with a concomitant increase in CK 24 hours post (Twist et al., 2005), suggesting that high intensity running performance may have been affected by muscle damage. Furthermore, Marcora and Bosio (2007) reported that strength training impaired running time-trial performance although RE was unaffected 24 hours post. Collectively, the attenuation of running performance following strength training may be dependent on the recovery period between each mode of training session and the intensity of running performed. However, applying such findings to concurrent training is at present difficult since running performance measures were examined following a single strength training session. In order to ascertain whether adaptation is determined by the acute responses of each mode of training session, it is essential to examine daily acute responses during a concurrent training program.

In a study that examined the effects of performing eccentric contractions for 7 consecutive days on muscle damage (Chen et al. 2001), it was found that eccentric training induced muscle damage as indicated by an increase in myofibre proteins (e.g. CK, lactate dehydrogenase) from days 3-6 although resided by day 7. Furthermore, ratings of muscle soreness increased from days 2-4 but returned to baseline by day 5. However, MVC was significantly reduced over the course of the study following the initial eccentric training session. Whilst symptoms of muscle damage were not exacerbated as a result of daily eccentric training, neuromuscular performance appeared to be compromised during the course of the study. These findings suggest that the quality of training sessions may be interfered by performing daily resistive-type exercises. However, the performance measures were limited to MVC tests and isokinetic exercises were performed over consecutive days on the same muscle group which is not typical of a strength training program.

In fact, novice and intermediate weight lifters have been recommended to train two to four days per week on the same muscle group to develop muscular –strength, –power and –endurance (Kraemer et al. 2002) (i.e. approximately 48 hours of recovery between each strength training session). On the other hand, moderate to high intensity endurance training sessions are commonly prescribed on consecutive days (Faude et al. 2009) or with strength training on the same day (Friel, 1998). Subsequently, it remains unknown whether strength training sessions performed on alternating days would affect the quality of daily endurance training sessions on consecutive days by measuring endurance performance. The purpose of the present study was to examine the effects of alternating-day strength training and consecutive-day endurance training on RE and running TTE over a 6-day period. It was hypothesised that running performance will be impaired over the entire 6-day period if alternating-day strength training is combined with consecutive-day endurance training.

9.2 Methods

Participants

Sixteen male and 8 female moderately trained runners were assigned into a CON group (8 males and 4 females) that undertook both strength and endurance training sessions and an ST group (8 males and 4 females) that only performed strength training sessions. The participants were matched for gender, fitness level and muscular strength between the CON and ST groups (**Table 9.1**). The participants were undertaking high intensity endurance training sessions (i.e. above 85% of predicted maximum heart rate) at least twice a week for the last 12 months and had not performed high intensity lower extremity strength training exercises (i.e. less than 12RM) 6 months prior to the commencement of the study. Biological variations were controlled by conducting the tests at the same time of day, participants wearing the same shoes for every test, refraining from high intensity physical activity for at least 24 hours prior to testing and refraining from caffeine– and food intake for at least 2 hours prior to testing. Participants were also required to maintain their training intensity and volume during the course of the study. However, participants were required to refrain from any form of physical activity during weeks 6 and 7 for the CON group and during week four for the ST group. Each participant completed informed consent before taking part in any testing procedures which were approved by the Institutional Human Research Ethics Committee and were run in accordance with the Declaration of Helsinki.

Table 9.1. The physical characteristics for the concurrent CON) and strength (ST) groups

Variables	**CON (n = 12)**	**ST (n = 12)**
No. of males	8	8
No. of females	4	4
Age (yrs)	30.8 ± 6.9	27.5 ± 6.3
Height (m)	1.75 ± 0.1	1.70 ± 0.1
Body mass (kg)	74.7 ± 13.8	69.4 ± 10.0
VO_{2max} ($mL.kg^{-1}.min^{-1}$)	57.1 ± 8.5	59.9 ± 5.5
6RM leg press (kg)	229.6 ± 83.1	251.4 ± 56.8
6RM leg extension (kg)	67.7 ± 14.2	64.8 ± 12.6
6RM leg curls (kg)	34.8 ± 9.0	33.6 ± 9.0
Knee extensor torque (Nm)	282.5 ± 70.4	304.2 ± 67.0

VO_{2max} = maximal oxygen consumption; 6RM = 6 repetition maximum

Research design

The study was conducted across 7 weeks for the CON group. The first 5 weeks were used to allow familiarity with training and testing protocols. Specifically, a familiarization session and VO_{2max} test were conducted during the first week. The familiarization session consisted of a 6RM assessment for incline leg press, leg extension and leg curls. The 6RM assessment (Baechle et al. 2008) and VO_{2max} test (Doma et al. 2012) were conducted according to previously described methods. During week 2, three endurance training sessions were conducted with at least one day of recovery in-between for familiarity purposes. During weeks 3 and 4, three strength training sessions were conducted with at least four days of recovery in-between for flush out purposes (Nelson et al. 1990). During week 5, a fifth endurance training session was conducted with at least four days of recovery following the third strength training session with physiological parameters collected as baseline values (Base-End). The experimental days were conducted during week 6 and control days during week 7 (**Table 9.2**). At least five days of recovery were provided between the last endurance training session of the experimental days to the first endurance training session of the control days. The experimental days were carried out over 6 days consisting of three strength training sessions performed on alternating days and endurance training sessions on consecutive days. There were 9 hours of recovery between the strength and endurance training sessions on the first, third and fifth day. The control days were undertaken over four days consisting of three endurance training sessions during the first three days and MVC test on the fourth day. The control days were essential to determine whether endurance performance would be impaired as a result of endurance training over consecutive days. The study was conducted across four weeks for the ST group. The first three weeks consisted of a familiarization session, VO_{2max} test and three strength training sessions for flush out purposes. During week four, three strength training sessions were carried out on alternating days. Rating of muscle –soreness (RMS) and –fatigue (RMF), using a 1-100 visual analogue scale (Chen et al. 2009), and MVC were collected prior to Base-End and prior to every strength and endurance training sessions during weeks 6 and 7 for the CON group and prior to the strength training sessions during week four for the ST group. All equipment was calibrated prior to any testing procedures. Running performance measures were collected during the endurance training sessions. The MVC tests were conducted and RMS and RMF were collected prior to each strength and endurance training session.

Table 9.2. An example of a training schedule of a participant in the concurrent group during the experimental days in week 6 and control days in week 7

Experimental days (Week 6)

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
7am	St		St		St	
5pm	End	End	End	End	End	End

Control days (week 7)

	Monday	Tuesday	Wednesday	Thursday
5pm	End	End	End	MVC

St = strength training session; End = Endurance training session; MVC = maximal voluntary contraction test

Endurance training sessions

The endurance training session consisted of a discontinuous incremental RE test, running intervals and TTE. The endurance training session was constructed in such a way to elicit an endurance training stimulus whilst collecting running performance measures. The protocol was separated into three stages with participants running at 70– and 90% of the VT_2 for ten minutes during the first two stages (**Figure 9.1**). During the third stage, four sets of intervals were undertaken followed by TTE at 110% of VT_2. The VT_2 for each participant was determined by identifying the inflection point of ventilation with respect to carbon dioxide production on a scatter diagram (Neder et al. 2006) from the VO_{2max} test. Oxygen consumption was collected (Powerlab ML206, Australia) to determine C_R, expressed as VO_2 relative to body mass raised to the power of 0.75 and metre ($mL.kg^{-0.75}.m^{-1}$), which was averaged during the last 5 minutes of the first two stages with peak C_R determined during TTE. The C_R was selected to report VO_2 as it has been reported to minimise inter-individual variability (Helgerud et al. 2001). Rating of perceived exertion was collected during the 9th minute of the first two stages and every minute during TTE. The RPE of the middle time points during the shortest TTE of a given endurance training session during the experimental days was used for comparisons (e.g. if 5 minutes was the shortest TTE of a given endurance training session during the experimental days, then RPE for the third minute of TTE of each endurance training session was compared to Base-End). For the subsequent sections of the paper, RPE collected during the three stages will be reported as RPE 1, RPE 2 and RPE 3, respectively.

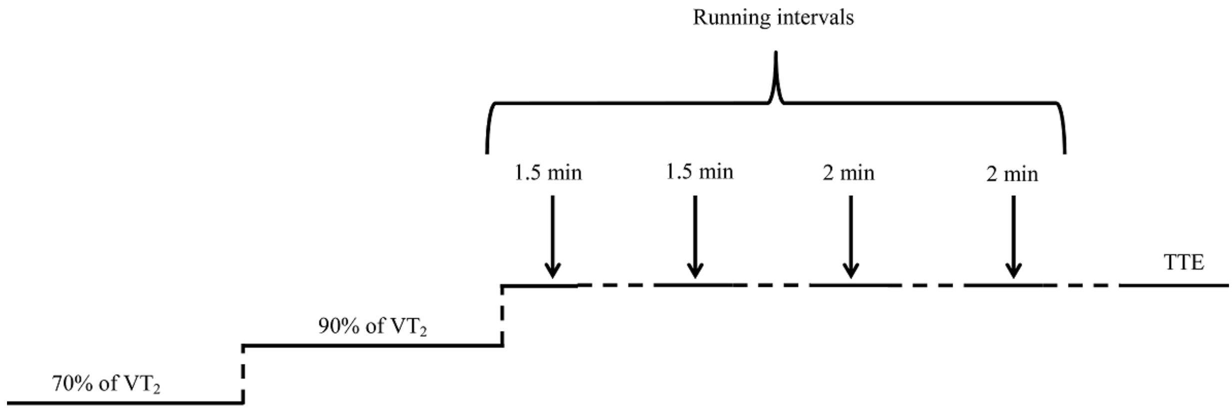

Figure 9.1. The discontinuous incremental endurance training session consisting of three stages at 70–, 90– and 110% of the second ventilatory threshold (VT_2), respectively, with time to exhaustion (TTE) during stage three. The dashed lines indicate 2 minute passive recovery periods

Strength training session

During the strength training sessions, exercises were performed in the order of incline leg press (Maxim MF701, South Australia, Australia), leg extension (Maxim MF701, South Australia, Australia) and leg-curls (Maxim MF701, South Australia, Australia). There were 6 sets for the incline leg press and four sets for the leg extension and leg curls, respectively, with three minutes of rest between each set and exercise to minimise accumulation of fatigue. The intensity of each exercise was set at 6RM for each strength training session.

Maximal voluntary contraction test

Three isometric contractions were conducted for knee extensor torque on a custom-built dynamometer chair (James Cook University, Australia). Each contraction was held for three seconds with 1.5 minutes of rest between each contraction (Doma & Deakin, 2012). The dynamometer chair was calibrated by placing a known weight on the force transducer. The force transducer was attached superior to the medial and lateral malleoli with the knee joint positioned at 110°. Of the three contractions, the largest torque averaged over the 6 second contraction was selected.

Sample size

An in-house pilot study on the reliability of the RE test and MVC test previously showed small within-participant CV for C_R, RPE, torque production and TTE (CV = 2.5–, 3.6–, 8.3– and 9.2%, respectively) amongst moderately endurance trained men (n = 14) (Doma, Deakin, Leicht, & Sealey, 2012). According to a nomogram for the estimation of measurement error with the use of CV (statistical power of 90%) (Atkinson et al. 2006), the percentage WD for the current sample size (n = 12) for C_R, RPE, torque production and TTE were found to be 3–, 4.5–, 10– and 11%, respectively. These percentage differences are smaller to previous reports that have shown significant differences in the oxygen cost of running (Palmer et al. 2001), RPE (Doherty et al. 2004), torque production (Doma & Deakin, 2012) and TTE (Esposito et al. 2012) as a result of a particular intervention.

Statistical analysis

The measure of central tendency and dispersion are expressed as mean ± SD. For within group comparisons of the CON group, one-way repeated measures analysis of variance ANOVA were used to determine differences in C_R, RPE and TTE between the Base-End and the endurance sessions during the experimental days and the endurance sessions during the control days. Paired T-tests were used to compare C_R, RPE and TTE between Base-End and the first day of the control days in order to determine whether adaptation or learning effects occurred as result of the 6 endurance training sessions during the experimental days. For the CON and ST groups, a two-way (time x group) repeated measures ANOVA was used to compare MVC measures, RMS and RMF. Unpaired T-tests were conducted to compare the physical characteristics between the CON and ST groups. When a significant effect was found, pair-wise comparisons with Bonferroni's adjustments were used to determine the location of the difference with the alpha level set at 0.05. All data was analysed using the Statistical Package for Social Sciences (SPSS, version 20).

9.3 Results

No significant differences were found in C_R ($P \geq 0.05$) and RPE ($P \geq 0.05$) during the first two stages and during TTE ($P \geq 0.05$) between Base-End and the first day of the control days ($P \geq 0.05$), indicating minimal effects of learning or adaptation from the experimental days. During the experimental days, no significant differences were found in C_R at stages 1 and 2 and at TTE ($P \geq 0.05$) and for RPE at stages 1 and 2 ($P \geq 0.05$) (**Figure 9.2**). However, a significant increase in RPE was found during the fourth and fifth day at TTE ($P < 0.05$). The

TTE during the experimental days were significantly less ($P < 0.05$) compared to Base-End (**Table 9.3.**).

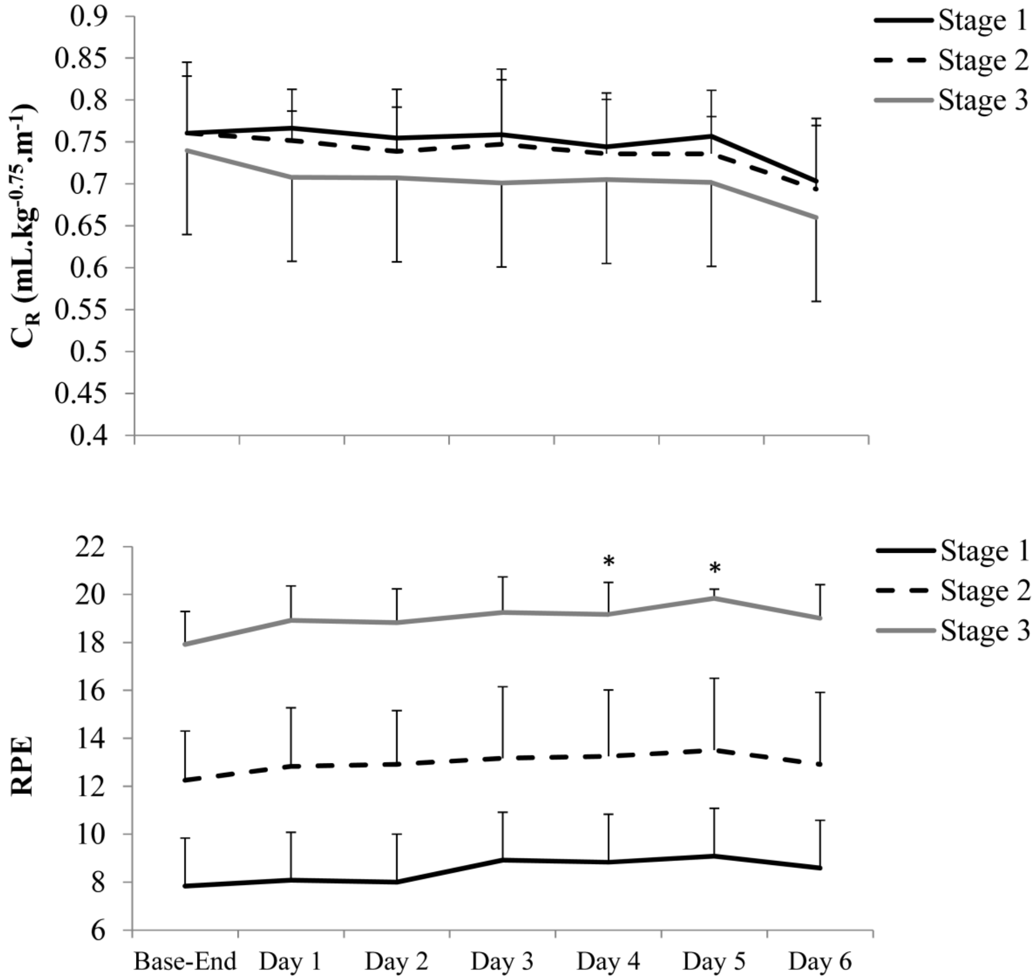

Figure 9.2. The oxygen cost of running (C_R) and rating of perceived exertion (RPE) collected during the baseline endurance training session (Base-End) and during the experimental days (Days 1, 2, 3, 4, 5 and 6, respectively) at Stages 1, 2 and 3

* Significantly greater than Base-End during Stage 3 ($P < 0.05$)

For the MVC collected prior to the endurance training sessions during the experimental days, torque was significantly reduced during the experimental days ($P < 0.05$) except for the fourth day ($P \geq 0.05$) (**Table 9.3**). RMS and RMF collected prior to the endurance training sessions during the experimental days was significantly greater compared to that collected prior to Base-End ($P < 0.05$) (**Table 9.3**).

When comparing the endurance training sessions during the control days, no significant differences were found in C_R, RPE (**Figure 9.3.**) and TTE ($P \geq 0.05$) (**Table 9.4**). Furthermore, no significant differences were found for torque, RMS or RMF ($P \geq 0.05$) (**Table 9.4**).

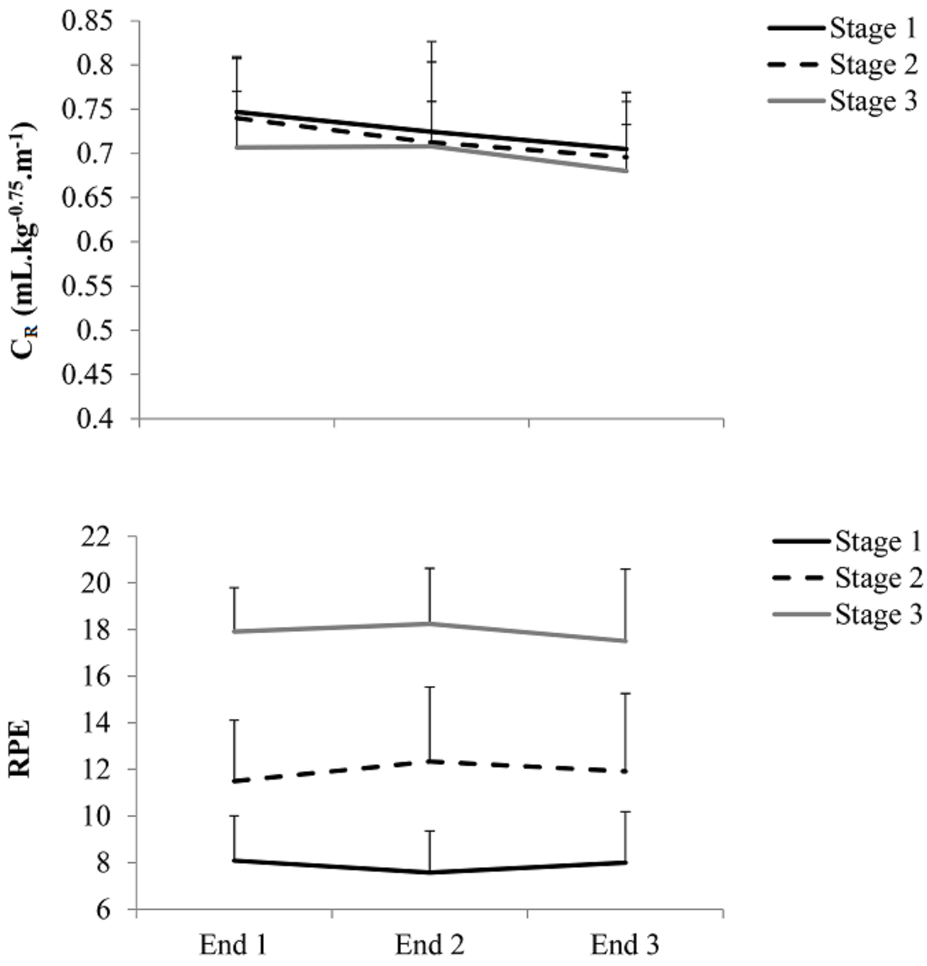

Figure 9.3. The oxygen cost of running (C_R) and rating of perceived exertion (RPE) during Stages 1, 2 and 3 for endurance training sessions 1, 2 and 3 (End 1, 2 and 3, respectively) during the control days

Table 9.3. The mean ± standard deviation of time to exhaustion (TTE), knee extensor torque (KET), rating of muscle soreness (RMS) and muscle fatigue (RMF) collected prior to the baseline endurance training session (Base-End) and the endurance training sessions during the experimental days (Days 1, 2, 3, 4, 5 and 6, respectively)

	Base-End	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
TTE (sec)	432.6 ± 143.4	315.7 ± 146.7*	320.7 ± 128.2*	294.2 ± 119.6*	314.9 ± 132.8*	273.8 ± 102.1*	301.1 ± 100.5*
KET (Nm)	321.5 ± 70.6	277.5 ± 64.1*	278.8 ± 64.0*	268.9 ± 64.2*	267.5 ± 69.1	265.0 ± 63.6*	271.7 ± 67.5*
RMS	6.3 ± 10.9	22.6 ± 15.6†	48.3 ± 24.0†	46.3 ± 21.2†	35.9 ± 24.5†	36.6 ± 24.9†	26.9 ± 23.0†
RMF	8.1 ± 13.7	33.2 ± 18.1†	44.4 ± 22.9†	49.0 ± 22.7†	40.5 ± 27.0†	40.6 ± 20.3†	33.3 ± 20.6†

* Significantly less than Base-End ($P < 0.05$)

† Significantly greater than Base-End ($P < 0.05$)

Table 9.4. The mean ± standard deviation of time to exhaustion (TTE), knee extensor torque (KET), rating of muscle soreness (RMS) and muscle fatigue (RMF) collected prior to the endurance training sessions during the control days on Days 1, 2 and 3 and KET, RMS and RMF collected on Day 4

	Day 1	Day 2	Day 3	Day 4
TTE (sec)	403.2 ± 197.6	416.9 ± 204.3	437.9 ± 208.2	–
KET (Nm)	285.9 ± 74.0	298.1 ± 88.1	306.7 ± 89.9	308.3 ± 69.3
RMS	7.8 ± 7.4	10.2 ± 8.9	10.0 ± 8.2	10.7 ± 9.7
RMF	9.6 ± 10.5	12.8 ± 8.7	13.8 ± 10.8	14.8 ± 9.9

No significant differences were found in the physical characteristics between the CON and ST groups ($P \geq 0.05$). For the MVC tests conducted prior to the strength training sessions, no group x time interaction effect was found for torque ($P \geq 0.05$) although torque was significantly reduced prior to the second and third strength training sessions for the CON group ($P \geq 0.05$) (**Figure 9.4**).

A group x time interaction effect was found for RMS and RMF ($P < 0.05$) with that collected prior to the second and third strength training sessions being significantly greater for the CON group compared to the ST group ($P < 0.05$) (**Figure 9.4**). For the CON group, the RMS and RMF were significantly greater when collected prior to the second and third strength training sessions compared to the first strength training session ($P < 0.05$) (**Figure 9.4**).

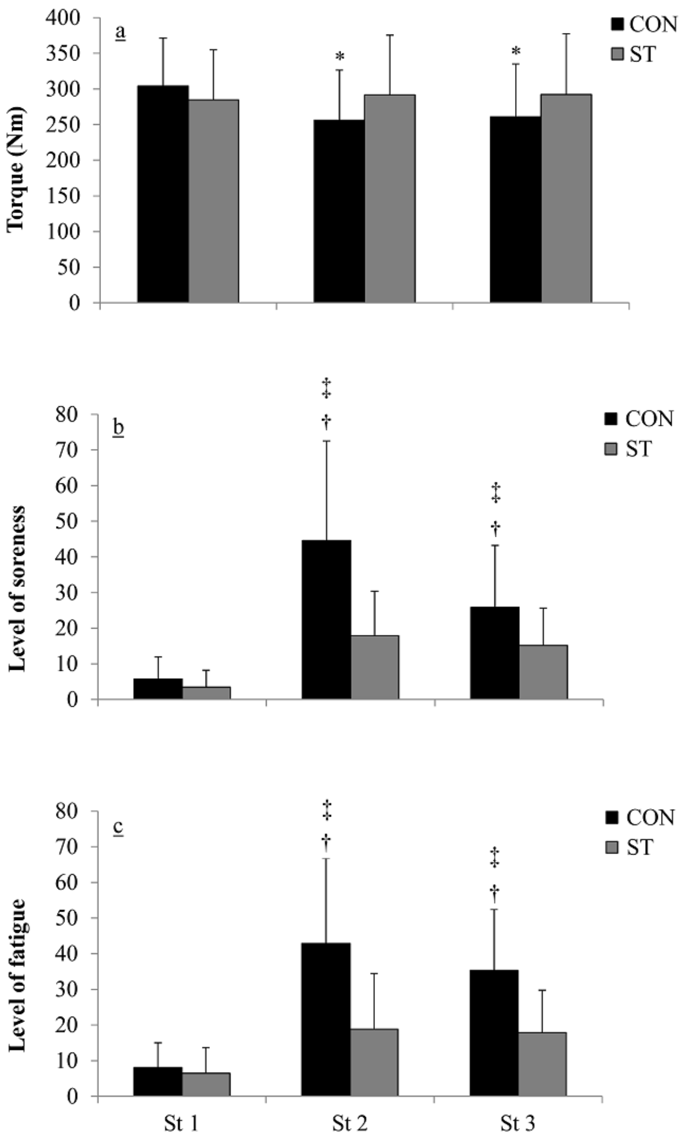

Figure 9.4. The knee extension torque (a), rating of muscle –soreness (b) and –fatigue (c) measured prior to the first, second and third strength training sessions (St 1, St 2 and St 3, respectively) for the concurrent training (CON) and strength training (ST) groups

* Significantly less than St 1 ($P < 0.05$)

† Significantly greater than St 1 ($P < 0.05$)

‡ Significantly greater than the ST group ($P < 0.05$)

9.4 Discussion

Strength training has been suggested to repetitively impair the quality of subsequent endurance training sessions during a concurrent training program thereby attenuating endurance adaptation (Chtara et al. 2005). The current study is the first to systematically test this hypothesis by examining running performance during 6 days of what would commonly be prescribed as a micro-cycle of a concurrent training program. The results showed that strength training on alternating days in conjunction with endurance training on consecutive days significantly impaired running performance at maximum effort (i.e. TTE), however, sub-maximal running performance (i.e. C_R) was unaffected.

During the experimental days for the CON group, TTE was significantly reduced when compared to Base-End and knee extensor torque was consistently reduced during the 6-day period. However, no significant differences were found in TTE and knee extensor torque between the endurance training sessions during the control days. Furthermore, knee extensor torque was significantly less whereas RMS and RMF were significantly greater prior to the strength training sessions for the CON group although these measures showed no differences for the ST group. Consequently, endurance training sessions on consecutive days or strength training sessions on alternating days does not appear to affect neuromuscular performance. In contrast, strength training prescribed on alternating days in conjunction with endurance training on consecutive days may generate an accumulation effect of fatigue as indicated by a sustained reduction in torque prior to the endurance training sessions, and as a result, may have impaired running performance at maximum effort. Although some studies have reported that sub-maximal endurance exercises accelerate recovery from exercise-induced fatigue

(Faude et al. 2009; Fujita et al. 2009), the present findings suggest that a combination of moderate to high intensity endurance exercise compromises recovery dynamics and increases the duration of fatigue initiated by strength training.

Chtara and colleagues (2005) reported sub-optimal improvement in 4 km running time trial performance when strength preceded endurance training sessions. The authors postulated that fatigue generated from strength training may have impeded on the physiological process of optimizing endurance adaptation. Furthermore, Nelson et al (1990) reported a less than optimal increase in VO_{2max}, mitochondrial density and concentration of citrate synthase and myokinase for the CON group compared to the END group. The authors suggested that hypertrophic adaptations may have contributed to diluting proteins essential for optimizing endurance adaptation. In light of the findings by Chtara et al (2005), Nelson et al (1990) and the current study, sub-optimal endurance adaptation as a result of concurrent training could be due to the combination of the accumulation of fatigue generated by the acute responses of each mode of training session which may repetitively impair training stimuli (Chtara et al., 2005) as well as the chronic responses being antagonistic between strength and endurance training (Nelson et al., 1990).

The reduction in TTE during the experimental days with concomitant reductions in torque prior to the endurance training sessions suggest that an accumulation of neuromuscular fatigue may have been present due to insufficient recovery between each mode of training. No significant difference was found in torque prior to the fourth endurance training session. A closer examination of the data indicates that two participants (i.e. one male and one female) experienced an increase in torque on the fourth day that is suspect to rendering a non-significant reduction. However, given the notable reduction (i.e. 16.8%) in average torque on the fourth day when compared to that collected prior to Base-End, it is reasonable to assume that neuromuscular fatigue may have contributed to reducing TTE during the experimental days. Previous studies have reported attenuation in running performance in conjunction with a reduction in muscle force generation capacity (Chen et al. 2009; Chen et al. 2007; Marcora et al. 2007). For example, Chen and colleagues (2007) showed impaired RE for five consecutive days following downhill running with reduction in maximal isometric force production of the knee extensors and lower extremity range of motion. The authors suggested that downhill running may have caused detrimental effects on neuromuscular function, and as a result, altered running kinematics. Whilst running kinematics were not examined in the present study, neuromuscular fatigue generated by strength and endurance training sessions may have caused inefficiency in running gait due to biomechanical modifications, resulting in impaired running performance at maximum effort (i.e. TTE).

The current investigation found no significant effect on C_R although TTE was significantly reduced during the experimental days when compared to Base-End. These findings are similar to Marcora et al (2007) who reported a significant reduction in running time trial performance with no effect on RE 24 hours following repetitive vertical jump exercises. Furthermore, studies have shown that resistive-type exercises caused no effect on RE (Paschalis et al. 2005; Scott et al. 2003) although running sprint ability was impaired (Twist et al. 2005) 24 hours post despite EIMD. Whilst these studies examined acute responses following a single training session over 1-2 days as opposed to multiple training sessions over a 6-day period in the current study, running performance at maximum effort appears to be more susceptible to attenuation than sub-maximal running performance. Chen et al (2009) showed that RE was impaired for five days following downhill running at 90% of VO_{2max}, however, RE was unaffected at 70% of VO_{2max}. The authors postulated that running performance at high intensity may have been compromised due to differences in neural recruitment patterns as a result of muscle damage. It has been suggested that type 2 fibers are predominantly recruited when running above AT (Abernethy et al. 1990). Furthermore, it has been documented that type 2 fibers are more susceptible to muscle damage than type 1 fibers (Connolly, Sayers, & McHugh, 2003). Subsequently, strength training may have compromised optimal neural recruitment of type 2 fibers essential for running above AT in the study by Chen et al (2009) and in the current study (i.e. TTE at 110% of VT_2). This is further supported by a reduction in torque as well as a significant increase in RMS and RMF during the 6 experimental days in the current study, indicating that muscle damage may have contributed to attenuation in running performance at high intensity (i.e. TTE). The increase in RPE at TTE during the fourth and fifth days of the experimental days also suggests that muscle damage may have impaired running performance. Scott et al (2003) reported no difference in RE 24 hours post strength training, although RPE and muscle soreness were increased. The authors postulated that local muscle pain could be associated with stiffness, decreased range of motion and the inability to produce optimal force which increases perception of effort. Subsequently, muscle soreness may have contributed to an increase in RPE, and as a result, impaired running performance at maximum effort in the current study.

In summary, performing strength training sessions on alternating days in conjunction with endurance training sessions on consecutive days does not affect sub-maximal running performance (i.e. C_R). In addition, strength training sessions on alternating days and endurance training sessions on consecutive days alone does not impair neuromuscular performance. However, performing these modes of training in conjunction with each other appears to induce neuromuscular fatigue and impair running performance at maximum or near maximum effort.

From a practical standpoint, the present findings suggest that the quality of high intensity endurance training sessions may be compromised during concurrent training by prescribing the timing, mode, intensity and volume of strength and endurance training sessions similar to the current study. In order to minimize fatigue during concurrent training, greater recovery periods should be incorporated between strength and endurance training sessions and/or to manipulate the intensity and volume of training for moderately trained runners. Subsequently, coaches and health practitioners are encouraged to apply the current findings as an initial basis of a concurrent training program and manipulate the training variables in accordance to the athletes' response and training adaptation.

Chapter 10

10.1 Summary

The majority of the concurrent training studies thus far have focused on the chronic adaptation over weeks of training (Chtara et al., 2008; Gravelle & Blessing, 2000; Glowacki et al., 2004) with minimal emphasis on the acute effects of combining strength and endurance training sessions in the one training program. Furthermore, the few studies that have examined the acute effects of concurrent training have been primarily limited to the impact of endurance exercises on strength training performance (Bentley et al., 1998; Bentley et al., 2000). To date, little is known of the acute impact of strength training on endurance performance. Subsequently, the current project systematically examined the impact of altering strength training variables on running performance. The current results have demonstrated that the impact of strength training on running performance was dependent on the training variables utilised (i.e. intensity/volume, contraction velocity and sequence of the mode of training and training frequency) as outlined below.

Chapter 6 showed that TTE following HW and HL (i.e. 6RM) sessions were significantly less compared to the LW sessions during a 6 hour recovery period. Furthermore, Chapter 9 reported a significant reduction in TTE 10 hours following a high intensity strength training session. Whilst strength training intensity was not varied during Chapter 9, the findings from Chapters 6 and 9 suggest that high intensity strength training causes a detrimental effect on running performance at maximum effort on the same day.

The results of Chapter 6 showed that RE was not affected following HW, HL and LW sessions with a 6 hour recovery period between the strength training sessions and the subsequent RE tests. However, the strength training session in Chapter 7 caused a significant increase in C_R and RPE despite similar recovery periods to Chapter 6 (i.e. 6 hours). In addition, MVC returned to baseline values 6 hours following the HW, HL and LW sessions in Chapter 6 although MVC was significantly less 6 and 9 hours following the strength training session in Chapters 7-9, respectively. The discrepancy in findings for C_R and MVC between Chapter 6 and Chapters 7-9 may be attributed to differences in training volume of the strength training sessions. The lower extremity strength training exercises during the HW, HL and LW sessions in Chapter 6 were limited to 6 sets of an incline leg press exercise. In contrast, the strength training session in Chapters 7-9 had considerably greater volume of training which consisted of 6 sets of an incline leg press exercise in conjunction with four sets of leg extension and leg curls, respectively. Subsequently, the recovery and fatigue dynamics following strength training appears to be influenced by training volume to a greater degree than training intensity.

In fact, it has been suggested that strength training volume facilitates strength development by enhancing efficiency of neural recruitment patterns (Cannon & Marino, 2010; Marshall, et al., 2011; Robbins, Marshall, & McEwen, 2012). Indeed, strength training volume has been shown to affect neural (Häkkinen, Komi, Alen, & Kauhanen, 1987; Häkkinen, et al., 1988), metabolic (Collins, Hill, Cureton, & DeMello, 1986) and hormonal responses (Gotshalk et al., 1997; Kraemer, 1988; Kraemer et al., 1991) as well as impact on satellite cells and myogenic regulatory factors (Hanssen et al., 2012). Furthermore, Haddock et al (2006) reported greater blood lactate levels following strength training exercises with three sets instead of a single set.

Subsequently, an increase in strength training volume appears to induce greater physiological stress, suggesting that longer recovery periods would be required post training before undertaking another training session.

In conjunction with strength training volume, the discrepancies in findings between Chapters 6 and 7 for C_R and RPE during the RE test may also be attributed to variations in contraction velocity of the strength training exercises. During Chapter 6, strength training exercises were performed with slow eccentric contractions. However, Chapter 7 consisted of self-paced strength training exercises which significantly increased C_R and RPE and caused alterations in running kinematics 6 hours post. These findings are in line with the study by Palmer and colleagues (2001), where VO_2 during a RE test significantly increased 8 hours following self-paced strength training. Previous studies have shown that fast– compared to slow eccentric contractions caused significantly greater reductions in isometric and dynamic torque productions with a concomitant increase in CK (Chapman et al., 2006; 2008). In addition, it has recently been reported that traditional exercises performed with fast– (i.e. 1 second for concentric– and eccentric components of the movement) compared to slow– (i.e. 6 seconds for concentric– and eccentric components of the movement) contractions caused greater reduction in strength (i.e. 1RM incline leg press) and power (i.e. counter movement jump) measures for up to 48 hours post (Ide et al., 2011). Whilst strength training exercises were performed with fast concentric and slow eccentric contractions in Chapter 6, the results by Ide and colleagues (2011) tends to suggest that neuromuscular performance measures are impaired to a greater extent following strength training exercises performed with faster contraction velocities. Subsequently, longer recovery periods may be required between each mode of training session when performing strength training exercises with faster contraction velocities.

In addition to the strength training variables (i.e. intensity, volume and contraction velocity), the amount of impact strength training has on running performance appears to be dependent on the intensity of running performance itself as highlighted by the three incremental stages of the RE test. The results from Chapters 6 and 9 showed that high intensity strength training had no effect on C_R and RPE during the first two stages of the RE test although TTE was significantly reduced 6– and 10 hours post, respectively. Further, TTE was significantly reduced although C_R was unaffected the day following strength and endurance training sessions during the RS-sequence in Chapter 8. During Chapter 7, the C_R and RPE were significantly greater at the second stage of the running session 6 hours following the strength training session although no differences were found during the first stage. Collectively, it appears that strength training causes detrimental effects on running performance to a greater degree above VT_2 (i.e. TTE). Previous studies have reported that a greater proportion of type 2 fibres are recruited during running above AT (Abernethy et al., 1990; Gollnick et al., 1974). In addition, high intensity eccentric contractions have been shown to cause greater muscle damage to type 2 compared to type 1 fibres (Fridén et al., 1983). Subsequently, the ability of type 2 fibres to contract may have been compromised at running speeds close to and above VT_2 as a result of strength training during the current studies.

Regarding training sequence, Chapter 8 showed that C_R for SR-RE was significantly greater than Base-RE and RS-RE whereas no differences were found between Base-RE and RS-RE during stages 1 and 2. In addition, H_{ROM} was significantly less during stages 1 and 2 and KF_S was significantly less during stage 2 for SR-RE compared to Base-RE although no differences were found in these kinematic variables between Base-RE and RS-RE. Furthermore, RPE during TTE was significantly greater during SR-RE compared to Base-RE. These findings indicate a sequence effect, where strength training performed prior to endurance training on the same day caused a greater impact on endurance performance the following day. The sequence of the mode of training in Chapter 9 was similar to Chapter 8, where strength training was performed prior to endurance training on the first, third and fifth day of the 6-day training period. The results showed that TTE was significantly reduced during each day of the 6-day training period. In light of the findings from Chapters 8 and 9, performing strength training exercises prior to endurance exercises on the same day appears to increase the duration of fatigue from one mode of training session the next over subsequent training days.

The accumulation effect of fatigue found in Chapter 8 during the SR-sequence was also shown in Chapter 9, where TTE was consistently attenuated with a concomitant reduction in torque measured prior to the endurance training sessions during the 6 experimental days for the CON group. Further, torque measured prior to the strength training sessions were also significantly reduced for the CON group. In contrast, no significant differences were found in torque measured prior to the strength training sessions for the ST group. These results suggest that high intensity endurance training sessions impairs recovery dynamics between strength training sessions performed on alternating days. Interestingly, the consecutive-day endurance training period during the control days for the CON group showed no accumulation effect of fatigue for neither torque nor running performance measures. Subsequently, according to the results from Chapters 7, 8 and 9, it appears that the combination of strength and endurance training may hamper the quality of endurance training sessions which in turn could induce sub-optimal endurance adaptation.

Whilst running performance at maximum effort (i.e. TTE) was impaired the following day when strength training preceded endurance training during Chapters 8 and 9, there were discrepancies in findings between these studies for sub-maximal running performance (i.e. C_R). Chapter 8 showed that C_R significantly increased for SR-RE during stages 1 and 2. However, C_R was unaffected during the RE tests conducted on the second, fourth and sixth day of the 6-day training period in Chapter 9. The disparity in findings between Chapters 8 and 9, despite similar training sequences and exercises prescribed, may be attributed to differences in the recovery period between strength and endurance training sessions performed on the same day as well as the timing of the RE test conducted the following day. A 6-hour recovery period was employed between the strength and endurance training session in Chapter 8 as opposed to a 9-hour recovery period in Chapter 9. Thus, the running session may have induced additional stress generated from the strength training session in Chapter 8 during the SR-sequence, and as a result, increased C_R the following day. In contrast, a 9-hour recovery period following strength training may have reduced the cumulative effects of fatigue to limit the detrimental effects on sub-maximal running performance the following day in Chapter 9. If the recovery period between strength and endurance training sessions incorporated in Chapter 9 was reduced to 6 hours, an increase in C_R may have been found over a 6 consecutive day period. Subsequently, the extent of the accumulation of fatigue and its effect on running performance may be dependent on the length of the recovery period between each mode of training session.

10.2 Practical applications

The attenuation in running performance (i.e. C_R, RPE and TTE), MVC and elevation in muscle –soreness and –fatigue reported by the current series of studies suggest that athletes need to consider the structure of their training program to undertake concurrent training at an optimum level. Subsequently, several practical applications have been generated for athletes and coaches to be implemented in a concurrent training program in order to limit potential fatigue, enhance the quality of strength and endurance training sessions and optimise training stimuli for adaptation:

1. According to the current findings, the recovery period between each mode of training session appeared to be dependent on the training variables utilised. Strength training exercises prescribed at higher intensity and volume with eccentric contractions performed at a self-selected pace impaired running performance and MVC to a greater extent than strength training exercises prescribed at lower intensity and volume with slower eccentric contractions (Chapters 6-9). In addition, the susceptibility to attenuation in running performance as a result of preceding strength and/or endurance training sessions was greater at faster running speeds. Subsequently, greater recover periods should be considered between strength and endurance training sessions when: 1) incorporating strength training sessions at high intensity and/or volume, 2) performing strength training exercises with faster (< four seconds) eccentric contractions and/or 3) conducting high intensity endurance training sessions.
2. Chapter 6 showed that strength training with slow eccentric contractions did not affect neither C_R nor RPE regardless of training intensity (i.e. HW versus LW sessions) or

volume (i.e. HW versus HL sessions) 6 hours post. Chapter 8 showed that C_R and RPE significantly increased 6 hours following strength training exercises using a self-paced strategy. However, Chapter 9 showed that strength training exercises identical to that of Chapter 8 showed no effect on C_R 9 hours post. Subsequently, sub-maximal endurance training sessions could be performed within the hours of strength training exercises performed with slow eccentric contractions. However, prescribing strength training sessions using a self-paced strategy with sub-maximal endurance training sessions on the same day should be avoided unless incorporating at least a 9 hour recovery period between each mode of training session. Given that reduction in TTE was consistently observed during each study, high intensity endurance training sessions should not be incorporated following lower extremity strength training sessions on the same day regardless of the type of strength training variables.

3. Similar to findings from Chapter 7, C_R and RPE significantly increased whereas H_{ROM} and KF_S significantly decreased the day following the SR-sequence when compared to Base-RE and RS-RE, although these parameters showed no differences during the RS-sequence when compared to Base-RE in Chapter 8. However, TTE was significantly reduced for both the SR-sequence and RS-sequence. In light of these results, it is recommended that sub-maximal running sessions are avoided the day following strength and endurance training as per the SR-sequence. On the other hand, minimal residual fatigue may be experienced during sub-maximal running sessions the day following endurance and strength training sessions as per the RS-sequence. However, maximal running sessions should be avoided the day following strength and endurance training sessions which are separated by several hours, regardless of training sequence, given that TTE was significantly reduced during SR-RE and RS-RE.

4. According to the overall findings, in order to avoid an accumulation effect of fatigue during concurrent training, high intensity lower extremity strength training sessions (i.e. ≥ three exercises at ≤ 6RM) and running sessions consisting of both moderate and high intensity intervals (i.e. 75-100% of maximum effort) need to be prescribed on alternating days. In so doing, at least 48 hours of recovery should be provided between each mode of training. Other methods of pre-empting levels of fatigue are to manipulate the intensity and volume of training for moderately trained and trained runners. Such strategies may include the reduction of intensity (i.e. > 6RM) and volume (i.e. < three exercises) of lower extremity strength training given that strength training appeared to cause greater decrement of neuromuscular performance than endurance training as shown in Chapter 8. According to the findings in both Chapters 8 and 9, when undertaking lower extremity strength training sessions at 6RM on alternating days and running sessions at moderate to high intensities on consecutive days, sequencing the mode of training by performing sub-maximal running sessions (i.e. moderate to high intensity) by at least 6 hours prior to strength training sessions may alleviate the cumulative effects of fatigue that was present in Chapter 9 although this warrants further investigation. However, the volume and intensity during the study in Chapter 9 was constant in order to examine the compatibility of strength and endurance training. Therefore, caution should be taken when prescribing linear and/or non-linear periodization programs since alteration in intensity and volume may have an impact on fatigue dynamics.

10.3 Recommendation for future research

Topics that warrant further investigation based on the current findings include:

1. Strength training variables

   – Chapter 6 showed that strength training exercises with slow eccentric contractions do not affect C_R regardless of training –intensity or –volume. Whilst Chapters 7, 8 and 9 examined the effect of strength training on running performance using a self-paced strategy, the effect of varying contraction velocity on running performance was not examined in the one study. Subsequently, it would be interesting to examine variations in eccentric contraction velocity (fast versus slow) on RE and TTE. In addition, given that the strength training methodology was standardized during studies in Chapters 7-9 and appeared to have a greater effect on running performance than the study in Chapter 6, a systematic investigation of altering strength training intensity and volume using self-paced strategies on running performance is also warranted.

2. Mode of endurance performance

   – The mode of endurance performance incorporated in the current studies was running. Given that sports encompass various types of endurance exercises (e.g. cycling, rowing, swimming, skiing and skating), it is essential to examine the acute effects of strength training on other modes of endurance exercises. Such studies will enable findings to be applied to a wider athletic demography and enhance the scientists', coaches' and athletes' understanding of the compatibility between strength and endurance exercises from a concurrent training standpoint.

3. Recovery period

   – The studies in Chapters 6-9 examined the effect of strength training on running performance by varying training intensity and volume, sequence and frequency. According to the findings, recovery period appears to be an essential component determining fatigue and recovery dynamics. Subsequently, further studies could examine recovery period as a dependent variable whilst incorporating training –intensity, –volume, –sequence and –frequency as independent variables. Such studies could then examine the acute effects of varying recovery periods between strength and endurance training.

4. Accumulation effect of strength and endurance training

   – Chapter 9 examined the effects of alternating-day strength training and consecutive-day endurance training on running performance and showed that TTE and MVC were significantly reduced over a 6-day period. Subsequently, an accumulation effect appeared to be present when strength and endurance training sessions were combined on the same day with a 9 hour recovery period despite a 48-hour recovery period between each strength training session. From these findings, several other investigations could be conducted in order to enhance our understanding of the acute interaction between strength and endurance training. Sale and colleagues (1991) reported that interference of strength adaptation was minimised when strength and endurance training sessions were performed on alternating days compared to when each mode of training session was performed on the same day. However, the investigation of the acute effects of alternating strength and endurance training sessions on running performance over multiple days has not been conducted. Such a study may enhance the understanding of the effect of recovery period between modes of training on running performance. Future studies could also investigate the acute effects of consecutive-day endurance training sessions with various endurance training modes (e.g. running, cycling and rowing) performed in an alternating manner in conjunction with alternating-day strength training sessions on endurance performance. Such investigation would be beneficial for triathletes or for endurance athletes undertaking various modes of endurance exercises in a single training program as a cross-training method. Finally, to examine the relationship between the acute responses of training to chronic adaptations as a result of concurrent training as studies to date have only examined the chronic adaptation of concurrent training by conducting physiological assessments prior to, mid and following a given concurrent training program (Glowacki et al., 2004; Sale et al., 1991). Examining the acute responses of each strength and endurance training session over an entire week at various time periods in the training program (e.g. during the first, mid and last week of a concurrent training program) will bridge the gap between the acute responses of concurrent training and subsequent adaptation.

5. Training background

   – The participants incorporated in the series of studies either have had little experience in strength training or have not undertaken high intensity strength training for the last 6 months. It is well established that exposure to strength training exercises with minimal to no experience in strength training will result in considerable interruption to most body systems (Burt et al., 2013). However, by the second or third exposure, the physiological system becomes accustomed to the stress induced by strength training, known as the repeated bout effect (Burt et al., 2013). Furthermore, individuals who are heavily strength trained experiences little disruption to their body systems since they are accustomed to the stress generated by strength training exercises. Whilst the participants in the current series of studies were exposed to a number of strength training sessions prior to the experimental trials in order to minimise the repeated bout effect, future studies should examine the acute effects of strength training on various performance parameters in individuals with substantial strength training experience.

10.4 Conclusion

The purpose of this project was to examine the acute effects of various strength and endurance training methods on running performance from a concurrent training standpoint. According to the findings from the current series of studies, the impact that strength training and endurance training has on running performance appears to be dependent on the training variables, the sequence of the mode of training and the frequency of training sessions which ultimately governs the amount of recovery period required between each mode of training session. The summary of the findings from the project are as follows:

- strength training exercises impaired running performance to a greater extent when prescribed at a high intensity compared to low intensity, fast eccentric compared to slow eccentric contractions and a greater volume of training by increasing the number of exercises during a single training session;
- strength training prescribed prior to endurance training induced greater fatigue the following day compared to endurance training prescribed prior to strength training as indicated by an attenuation in running performance;
- strength training sessions performed on alternating days with endurance training on consecutive days caused detrimental effects on running performance as a result of an accumulation of fatigue; and

- attenuation of running performance as a result of fatigue induced by previous training sessions was greater at higher running speeds. Subsequently, the transfer of exercise-induced fatigue from one mode of training session to the next could be controlled by reducing the intensity and/or volume of strength and/or endurance training, to prescribe endurance training prior to strength training if performed on the same day or refraining from performing strenuous training sessions on the same day by providing longer recovery periods.

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Appendix 1 – Conference procedings

Appendix A

Doma, K., and Deakin, G.B. (2011). The effects of intensity and type of resistance training on muscle force generation capacity immediately and 6 hours post training. *Journal of Science and Medicine in Sport, 14*(Supplement1), e110.

Introduction

The assessment of muscle force generation capacity (MFGC) is effective in determining muscular fatigability following resistance training and its association to prevalence with injuries. Subsequently, the purpose of the current study was to examine the intensity and type of resistance exercises on MFGC immediately- and 6 hours post training.

Methodology

Male participants (n = 12) performed high intensity whole body (HW), low intensity whole body (LW) and high intensity lower body only (HL) sessions in random order across three sessions. Exercises for HW and LW sessions were performed in the order of inclined leg-press, bench press and flat bench rows whereas the HL session solely consisted of inclined leg-press. The upper body and lower body exercises were performed with 4 and 6 sets, respectively. Exercises for HW and HL sessions were performed with 6 reps and 3 minutes rest between each set whereas exercises for the LW session were performed with 20 reps with 1.5 minutes rest between each set. MFGC of the right knee extensors were assessed prior to, immediately- and 6 hours following each of the resistance training session with an isometric dynamometer. A two-way (session x time) Friedman test was used to determine differences in MFGC.

Results

Peak and average forces were significantly greater during pre- compared to immediately post LW session ($P < 0.05$) and average force was significantly greater during pre- compared to immediately post HL session ($P < 0.05$). No significant differences in peak and average forces were found between pre- and 6 hours following LW and HL ($P \geq 0.05$), between pre-, immediately- and 6 hours following HW ($P \geq 0.05$) and between LW, HL and HW for immediately- and 6 hours following training ($P \geq 0.05$).

Discussion and conclusion

A significant reduction in MFGC immediately following LW session indicates that a systemic effect was induced, exemplifying greater muscular fatigue compared to post HW session. Similarly, a significant reduction in MFGC following HL session was found despite comparable MFGC between pre- and immediately post HW session. These discrepancies in results may be because upper-body exercises were performed after leg-press causing a 30-minute window between the leg-press and the MFGC assessment for HW session. Subsequently, such findings indicate that physical activity may be performed immediately following high intensity- and 6 hours following high volume low intensity resistance training sessions constructed specifically for the current study with minimal risks of injuries.

Appendix B

Doma, K., and Deakin, G.B. (2011). The acute effects of strength training on running economy and lower extremity kinematics. Proceedings of the 8th Australasian Biomechanics Conference, Institute of Sport, Canberra, Australia.

Introduction

Whilst studies have shown that strength training (ST) can either impair (1) or have no affect on running economy (RE) (2), little is known of the effects of high intensity ST on running kinematics. Consequently, the purpose of this study was to examine running economy in conjunction with lower extremity joint kinematics 6 hours following a high intensity ST session.

Methods

Twelve trained and moderately trained runners (age 23.4 ± 6.4 years, height 1.8 ± 0.1m, weight 74.4 ± 8.3 kg) undertook a control RE test one week prior to a ST session (RE1) and another RE test 6 hours following a ST session (RE2). During the ST session, exercises were performed in the order of incline leg press with 6 sets of 6 repetitions and leg extension and leg curls with 4 sets of 6 repetitions. There were three minutes rest between each set. The RE test consisted of two 10-minute stages at an intensity of 70- and 90% of anaerobic threshold, respectively. There were two minutes rest between each stage. During the RE test, oxygen consumption (VO_2) was collected with a $K4b^2$ gas analyser. In addition, lower extremity joint kinematics were recorded for 10 strides using 8 VICON cameras (Oxford, UK, 100Hz) at 9 minutes 30 seconds of each stage. Running gait parameters included hip range of motion

(H_{ROM}), peak knee flexion during swing phase (KF_S), peak knee flexion after foot strike (KF_{AS}), and ankle range of motion (A_{ROM}). All variables were analysed using Paired-Sample T Tests.

Results

The H_{ROM} was significantly less and the A_{ROM} was significantly greater for RE2 compared to RE1 during the second stage ($P < 0.05$). No significant differences were found between RE1 and RE2 for the other variables during the first and second stages ($P \geq 0.05$).

Discussion and conclusion

Whilst VO_2 appears to not have been affected, high intensity ST reduced H_{ROM} which may have been due to an increase in the stiffness of hip flexor- and extensor- muscles (3). As limited morphological damage would have been induced on the ankle plantar- and dorsi-flexors from the ST exercises, A_{ROM} may have significantly increased during RE2 in order to compensate for insufficient mobility of the hips. Subsequently, caution should be used when interpreting the effects of ST on RE solely on physiological parameters.

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Appendix C

Doma, K., and Deakin, G.B. (2011). Kinematic comparisons between pre- and post-steady state running at various running speeds. Proceedings of the 8th Australasian Biomechanics Conference, Institute of Sport, Canberra, Australia.

Introduction

Studies have shown that lower extremity kinematics is affected during running at exhaustion due to fatigue (1, 2). However, it is unknown whether running kinematics is altered over the course of running prior to exhaustion, in particular, the transition from the commencement of running to steady state. Subsequently, the purpose of this study was to compare lower extremity kinematics between running conditions prior to and following the obtainment of steady-state at various running speeds.

Methods

Fourteen trained and moderately endurance trained runners (age 22.6 ± 3.5 years, height 1.8 ± 0.1m, weight 75.0 ± 8.0 kg) undertook a running economy (RE) test consisting of two 10-minute stages at an intensity of 70- and 90% of anaerobic threshold, respectively. There were two minutes rest between each stage. During the RE test, oxygen consumption was collected to ascertain whether the subjects reached steady-state. Lower extremity joint kinematics were recorded for 10 strides using 8 VICON cameras (Oxford, UK, 100Hz) at 30 seconds (T_{30}) and at 9 minutes 30 seconds ($T_{9:30}$) of each stage. Borg's rating of perceived exertion (RPE) was collected immediately following motion capturing of each stage. Running gait parameters included hip range of motion (H_{ROM}), peak knee flexion during swing phase (KF_S), peak knee flexion after foot strike (KF_{AS}), and A_{ROM}. All variables were compared between T_{30} and $T_{9:30}$ of each stage of the RE test using Paired-Sample T Tests.

Results

All subjects reached steady-state within three minutes of each stage. At $T_{9:30}$ of the second stage, RPE was less than 17, indicating the subjects did not reach exhaustion. When compared from $T_{9:30}$ to T_{30}, RPE and H_{ROM} were significantly greater during the first and second stages whereas K_{FS} and A_{ROM} were significantly greater during the second stage ($P < 0.05$) with no significant differences for KF_{AS} ($P \geq 0.05$).

Discussion and conclusion

The increase in joint ROM may be the result of improved joint mobility due to an increase in the visco-elasticity of the musculo-tendinous unit. Unlike previous findings (1, 2), the changes in kinematics during the transition from the commencement of running to steady state appear to be the result of optimising running technique and not the impact of fatigue.

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Appendix D

Doma, K., and Deakin, G.B. (2011). Investigation of running economy 6 hours post full body and lower body strength training. *Journal of Australian Strength and Conditioning, 20*(Supplement 1), 94-96.

Introduction

Exercise training programs that incorporate strength and endurance exercises in the one training program are known as concurrent training (Hickson, 1980). An array of research has shown that concurrent training induces sub-optimal strength and/or endurance training adaptation (Gergley, 2009; Izquierdo, Häkkinen, Ibanez, Kraemer & Gorostiaga, 2005; Bell, Petersen, Wessel, Bagnall & Quinney, 1991). It has been suggested that the attenuation in training adaptation in response to concurrent training may be due to the interference between strength and endurance training at an acute level (Leveritt & Abernethy, 1999). Indeed, studies have shown that endurance exercises reduces muscle force generation capacity (Bentley, Zhou & Davie, 1998; Leveritt, MacLaughlin & Abernethy, 2000), which may be an indicator for the deficit in strength training adaptation as a result of undertaking endurance training. However, there is limited investigation of the effects of strength training on endurance performance when conducted on the same day.

A study conducted by Palmer and Sleivert (2001) showed attenuation in running economy (RE) 8 hours following whole body strength training (i.e. upper and lower body). However, squats and dead-lifts were incorporated into the training program which are considered advanced and may compromise training adaptation and/or result in injury if performed incorrectly. Subsequently, such exercises may not be ideal for endurance athletes undertaking concurrent training. On the other hand, exercises using a leg press machine may be beneficial as the movements are controlled and require limited strength training experience. The simplicity of the technique when performing leg press exercises would also minimize inter-individual variability in a research context. In addition, Palmer and colleagues (2001) demonstrated that RE is impaired possibly due to systemic effects as a result of performing whole body strength training (WST). However, little is known of the local effects of strength training on RE by performing a lower body strength training (LST) session. Deakin (2004) found that the physiological cost of cycling increased three hours following a LST session using leg press exercises. Subsequently, exercises solely using a leg press machine, which would induce local effects, appear to impede endurance performance. However, given that cycling predominantly imposes physiological stress in the muscles of the lower extremity, the effect on RE may differ between strength training exercises that induce a systemic effect (i.e. WST session) as opposed to a local effect (i.e. LST session). Such investigation has not been conducted as far as the authors are aware. Consequently, the purpose of this study was to examine RE 6 hours following WST and LST sessions. It was hypothesized that WST and LST sessions will increase the oxygen cost of running and that the increase in oxygen cost of running will be greater following the WST session compared to the LST session.

Methods

Fifteen trained and moderately endurance trained male runners participated in the study. The physical characteristics of the subjects are shown in Table 1. Each subject completed informed consent before taking part in any testing procedures. All procedures in this study were approved by the Institutional Human Research Ethics Committee.

The study was conducted across four weeks. During the first week, a familiarisation session and a maximal aerobic uptake (VO_{2max}) test was conducted 2-3 days apart. The familiarisation session was used to allow subjects to familiarise themselves with the equipment and protocols as well as conduct 6 repetitions maximum (RM) assessments for the selected upper and lower body strength training exercises. Three days following the VO_{2max} test, a control RE test was conducted. The RE test was a discontinuous incremental protocol consisting of two 10-minute stages. The subjects ran at 70- and 90% of the second ventilatory threshold (VT_2) with two minutes passive recovery between each stage. During the last two weeks, the subjects underwent WST and LST sessions in random order separated by 7 days. Exercises performed during the WST session included incline leg press, bench press and flat bench rows whereas only incline leg press was performed during the LST session. The incline leg press was performed with 6 sets of 6 repetitions whereas the bench press and flat bench rows were performed with 4 sets of 6 repetitions. There were three minutes rest between each set and five minutes rest between each exercise.

All data are expressed as mean ± standard deviation and were analysed using the Statistical Package for Social Sciences (SPSS, version 18, Chicago, IL). One-way with one between subject factor (exercise order) repeated measures analysis of variance (ANOVA) was used to analyse the differences of VO_2 between the control RE test and the two RE tests 6 hours following the full body and lower body strength training sessions, respectively. In order to determine the location of the difference, Bonferroni's adjustments were used. The alpha level was set at 0.05.

Results

Between-subject comparisons indicated no significant differences for exercise order ($p \geq 0.05$), demonstrating that randomisation was successful. The results indicated that each subject reached steady-state within 3 minutes of the commencement of running for the first and second stages. No significant differences in VO_2 were found between the control RE test and the two RE tests following the WST and LST sessions during the first and second stages ($p \geq 0.05$) (Figure 1).

Table 1. Physical characteristics of the trained and moderately endurance trained runners

Variables	Subjects
Age (years)	23.67 ± 5.41
Height (metres)	1.79 ± 0.08
Mass (kg)	75.41 ± 10.04
VO_{2max} (mL.kg.min^{-1})	63.96 ± 5.75

VO_{2max} = maximal oxygen uptake

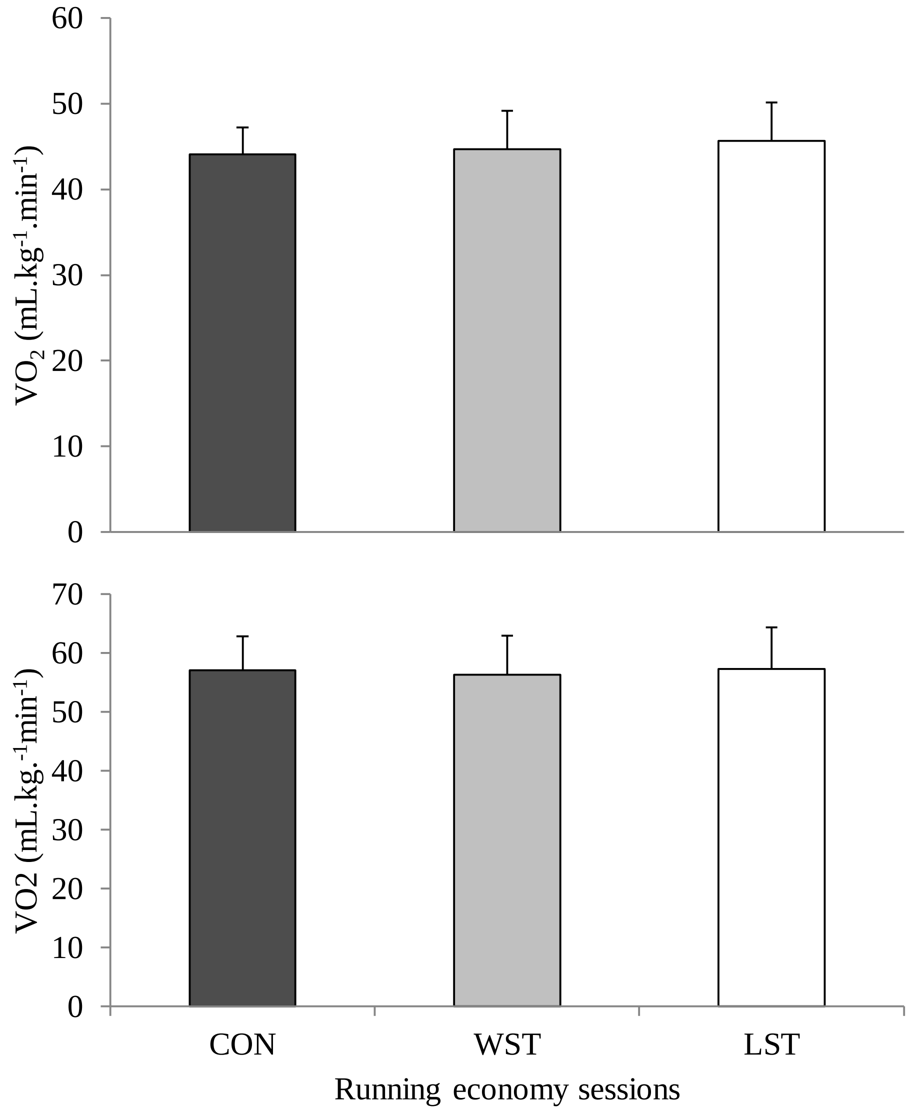

Figure 1. Oxygen consumption (VO_2 mL.kg.min^{-1}) averaged over the last 5 minutes of the control running economy test (CON), running economy following whole body strength training (WST) and lower body strength training (LST) during the first (top) and second (bottom) stages.

Discussion and conclusion

The results in the current study demonstrated that there were no differences in the oxygen cost of running following WST and LST session, rejecting the hypotheses. These findings demonstrate that RE is not affected 6 hours following strength training exercises selected for the current study.

The comparable oxygen cost of running between the control RE and the RE following WST and LST sessions found in the current study are not in agreement with previous findings that have shown an increase in the physiological cost of running following a WST session (Palmer et al., 2001) and cycling following a LST session (Deakin, 2004). In conjunction with an increase in the physiological cost of running and cycling, Palmer et al (2001) and Deakin (2004) demonstrated a concomitant reduction in muscle force generation capacity, indicating that attenuation in endurance performance may have been a result of fatigue. It is expected that the physiological cost will increase when running or cycling in a state of exercise induced muscular fatigue incurred by strength training exercises as the neuromuscular system of the lower extremity would not function optimally. The impairment of the morphological properties of the muscles following strength training would reduce the efficiency of movement and increase energy demands during endurance performance.

Differences in the findings by Palmer and colleagues (2001) may be due to the selection of strength training exercises. Palmer et al (2001) incorporated squats and dead lifts whereas the current study only included incline leg-press exercises. Whilst it has been shown that incline leg-press exercises alone impairs muscle force generation capacity (Deakin, 2004), it is expected that squats and dead-lifts would cause greater muscle damage as both exercises target the quadriceps, hamstrings and gluteal muscles. The discrepancies between the findings by Deakin (2004) and the present study may be attributed to differences in the mode of endurance exercise selected as a performance test (i.e. cycling versus running) and the recovery period between the strength training session and the endurance performance test. Given that the movements of the lower extremity during cycling mimics the exercises on the leg press machine, greater physiological stress may transfer from the leg press exercises to cycling than running. In addition, whilst 6 hours may provide sufficient recovery between strength and endurance training sessions, three hours appear to be insufficient as reported by Deakin (2004). Subsequently, the investigation of leg press exercises on cycling performance with a 6 hour recovery period warrants further investigation.

Practical applications

The findings in the current study indicated that WST and LST sessions do not affect oxygen cost of running at intensities of 70- and 90% of VT_2. Subsequently, strength training session can be conducted with minimal interference on running performance at sub-maximal intensities on the same day for trained and moderately trained runners. However, it is essential to provide a minimum of 6 hour recovery between the two modes of training sessions and that the intensity and type of strength training exercises from the current study are specifically incorporated in the strength training session.

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Appendix E

Doma, K., and Deakin, G.B. (2012). The acute effects of strength training on running performance over two consecutive days. 17th Annual Congress of the European College of Sport Science, Bruges, Belgium, 4-7th July, 2012.

Introduction

Strength training (ST) has been shown to impair running economy with an 8-hour recovery period (Palmer et al., 2001). Accordingly, ST may interfere with endurance adaptations by causing acute detrimental effects on endurance training stimuli. However, to determine whether there are cumulative effects of strength training on endurance training stimulus, it is essential to examine the acute effect of strength training on endurance performance over consecutive days. Subsequently, the purpose of this study was to examine the acute effects of strength training on running performance over two consecutive days.

Methods

Six male and four female moderately trained runners undertook two running performance tests (RP1 and RP2) 10- and 24 hours following a strength training session, respectively. A baseline running performance test (Base RP) was conducted at least two days before the ST session. Maximal voluntary contractions of the knee extensors were collected prior to and following the ST session and RP1 and RP2. The running performance test was a three stage discontinuous test with the first two stages set at 70- and 90% of ventilatory threshold (VT), respectively, for 10 minutes. The last stage was set at 110% of VT in order to record time-to-exhaustion (TTE). There were two minutes rest between each stage with oxygen cost (C_R) and blood lactate (BL) collected during and after the running performance test, respectively. The exercises during the ST session were performed in the order of incline leg press, leg extension and leg curls. All ST exercises were performed at 6 repetitions maximum with 6 sets for the incline leg press and four sets for the leg extension and leg curls, respectively, with three minutes rest between each set and exercise. A one way repeated measures analysis of variance was used to determine differences in performance variables.

Results

The TTE was significantly less during RP 1 and RP2 compared to Base RP ($P < 0.05$). In addition, MVC following the ST session and prior to and following RP 1 and RP2 were significantly less than the MVC prior to the ST session ($P < 0.05$). There were no significant differences in CR and BL between Base RP, RP 1 and RP2.

Discussion and Conclusion

The attenuation in running performance at maximum effort (i.e. TTE) over 2 consecutive days indicates that cumulative effects of fatigue may be induced as a result of performing one ST session. Such findings may be due to impaired muscular contractility as the knee extensor muscles did not recovery to baseline (i.e. MVC prior to the ST session). The comparable C_R between Base RP, RP 1 and 2 shows that strength training does not cause cumulative effects on running performance at sub-maximal levels. Subsequently, caution should be taken when generating training programs that consists of strength and endurance training sessions.

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Palmer, C.D., & Sleivert, G.G. (2001). Running economy is impaired following a single bout of resistance exercise. *Journal of Science and Medicine in Sport, 4*(4), 447-459.

Appendix F

Doma, K., and Deakin, G.B. (2012). The cumulative effects of strength and endurance training on running performance. National Strength and Conditioning Association Conference, Rhode Island, USA, 11-14th July, 2012.

Concurrent training has been shown to induce sub-optimal strength and endurance adaptations. It has been suggested that the interference in adaptation may be attributed to the cumulative effects of fatigue between successive training sessions, known as the "acute hypothesis". In order to have a better understanding of the mechanisms associated with the "acute hypothesis", it is essential to systematically examine the acute responses of each strength and endurance training session over successive days. PURPOSE: To examine the acute effects of endurance training over four consecutive days coupled with strength training on alternative days. METHODS: Six male and four female moderately trained runners who were familiarised with strength training took part in the study. Two days following a running session, subjects completed strength (ST) and running (RUN) sessions on the first and third day with 10 hours of recovery and a single RUN session conducted on the second and fourth day. Data was collected during the RUN session two days prior to the first ST session to determine baseline (Base-RP). Data was also collected during RUN sessions conducted on the second and fourth day to determine running performance (RP-1 and RP-2, respectively). Maximal isometric contractions (MIC) of the knee extensors were collected prior to the Base-RP, RP-1 and RP-2. The RUN session was a three stage discontinuous protocol with the first two stages set at 70- and 90% of ventilatory threshold (VT), respectively, for 10 minutes. The last stage was set at 110% of VT in order to record time-to-exhaustion (TTE). There were two minutes rest between each stage. The oxygen cost of running (C_R) was collected during RP-1 and RP-2 and blood lactate collected at the completion of TTE. During the ST training session, 6 sets of 6 repetitions of incline leg press exercises and 4 sets of 6 repetitions of leg extension and leg curls were performed. There were three minutes of rest between each set and exercise. A one way repeated measures analysis of variance was used to determine differences in performance variables. RESULTS: The TTE was significantly less during RP-1 and RP-2 compared to Base RP ($P < 0.05$). In addition, MIC prior to RP-1 and RP-2 were significantly less than the MIC prior to Base-RP ($P < 0.05$). There were no significant differences in CR and BL between Base-RP, RP-1 and RP-2. CONCLUSION: The results showed that endurance training over consecutive days in conjunction with strength training on alternative days caused attenuation in running performance at maximum effort (i.e. TTE). Such findings may be attributed to impaired muscular contractility as the knee extensor muscles did not recover to baseline (i.e. MIC prior to Base-RP). However, the incorporation of strength training to a daily endurance training regime does not appear to impair running performance at sub-maximal levels. PRACTICAL APPLICATION: The results in the current study demonstrate that the previously reported interference in training adaptation as a result of undertaking concurrent training may in part be attributed to the transfer of fatigue between various modes of training sessions. Consequently, a recovery period of more than one day between strength training sessions when combined with endurance training may be essential in order to minimize carry-over effects of fatigue and to optimize strength and endurance training adaptations.

Appendix G

Doma, K., and Deakin, G.B. (2012). The cumulative effects of strength and endurance training sessions on muscle force generation capacity over four days. *Journal of Australian Strength and Conditioning*, In press.

Introduction

The incorporation of strength and endurance training sessions in the one training program is known as concurrent training (CT) (11). Numerous studies have shown that CT induces sub-optimal strength adaptations (7, 10, 15). This incompatibility existent between strength and endurance training sessions is known as the "interference phenomenon" (15) and has been under scrutiny amongst scientists for over 30 years. As a result, several hypotheses have been proposed in an attempt to explain the interference of strength development due to CT. The chronic hypothesis suggests that the muscle is unable to undergo optimal metabolic and morphological adaptations since the physiological responses induced by endurance training are vastly different and sometimes antagonistic to strength training (5). The acute hypothesis contends that the residual effects of fatigue generated by previous endurance training sessions impairs muscular contractility and thereby attenuates training stimuli for optimal strength development (5). Indeed, it has been reported that moderate to high intensity 60-minute cycling sessions can impair muscle force generation capacity for 6 hours post (2), suggesting that the quality of strength training sessions may be compromised if undertaken within the hours of an endurance training session.

In addition to attenuation of strength development, studies have also shown sub-optimal endurance adaptations as a result of CT (7, 4). Chtara et al (4) examined the effects of the sequence of strength and endurance training on 4km running time-trial performance following 12 weeks of CT. The participants were allocated into groups that performed strength prior to endurance training (SE), endurance prior to strength training (ES) and endurance training only (E). The results showed that the improvements in 4km running time trial performance were better for the ES group compared to the SE and E groups. The authors suggested that the preceding strength training sessions may have compromised the quality of endurance training sessions, which may have contributed to attenuating endurance development. Indeed, it has been shown that strength training can impair muscle force generation capacity (MFGC) from 48 hours (14) to 9 days (3). Furthermore, it has been reported that running economy and running time-to exhaustion were impaired with a concomitant reduction in MFGC 6-8 hours following strength training (6, 19).

In light of the above, both strength and endurance training sessions may impair the quality of subsequent training sessions due to disturbance to the morphological properties of the muscle. However, the examination of the acute responses of strength and endurance exercises has been limited to a single training session. The systematic investigation of the impact of both strength and endurance training sessions on MFGC over multiple days during a typical CT program has not been conducted as far as the authors are aware. Examining the acute responses of strength and endurance training on MFGC over multiple days may shed light on the mechanisms associated with the interference of strength and/or endurance development. Subsequently, the purpose of the current study was to examine MFGC following strength and endurance training sessions over four consecutive days. It was hypothesized that MFGC will be compromised when strength and endurance training sessions are combined compared to when strength training sessions are completed alone.

Methods

A group of moderately trained runners, consisting of 16 males and 8 females, were evenly assigned into concurrent training (CT) (age 30.8 ± 6.9 years; height 1.75 ± 0.1 m; body mass 74.7 ± 13.8 kg; VO_{2max} 57.1 ± 8.5 $mL.kg^{-1}.min^{-1}$) and strength training (ST) (age 27.5 ± 6.3 years; height 1.70 ± 0.1 m; body mass 69.4 ± 10.0 kg; VO_{2max} 59.9 ± 5.5 $mL.kg^{-1}.min^{-1}$) groups. Each participant completed informed consent prior to taking part in any testing procedures. All procedures in this study were approved by the Institutional Human Research Ethics Committee.

The study was carried out across 6 weeks for the CT group. Week 1 was used to conduct a familiarization session and a VO_{2max} test for both the CT and ST groups. The familiarization session was used to allow familiarity with the protocols as well as to conduct a 6 repetition maximum (RM) assessment. For the CT group, four endurance training sessions were conducted during weeks 2 and 3 and three strength training sessions were conducted on weeks 4 and 5 for habituation. During week 6, participants undertook two strength training sessions on alternating days and four endurance training sessions on consecutive days (Figure 1). The study was completed over 4 weeks for the ST group. During weeks 2 and 3, three strength training sessions were conducted for habituation. During week 4, the ST group undertook two strength training sessions on alternating days across three days. Maximal voluntary contraction (MVC) tests for the knee extensors were conducted prior to week 6 as baseline and prior to each training session during week 6 for the CT group. For the ST group during week 4, MVC tests were conducted prior to the strength training sessions as well as the day in-between the two strength training sessions (i.e. the second day) (Figure 1). The MVC tests were essential to monitor the function of the neuromuscular properties and the level of fatigue as a result of performing concurrent training.

Figure 1. An example of training schedules for the strength (St) and endurance (End) training sessions conducted by a participant from the concurrent training (CT) group during week 6 and a participant from the strength training (ST) group during week 4, including days with no training sessions (Ns) and upward arrows denoting the timing of the maximal voluntary contraction tests.

The strength training session consisted of an incline leg press for 6 sets and leg extension and leg curls for 4 sets. The exercises were performed at 6RM with three minutes of rest in-between each set and exercise. The intensity of the strength session is identical to that performed during a previous study (6) and is in accordance to a commonly prescribed concurrent training program (8). The endurance training session was a three-stage incremental protocol on the treadmill with participants running at 70- and 90% of the second ventilatory threshold (VT_2) for ten minutes during the first two stages. The third stage was set at 110% of VT_2 and the participants ran four sets of running intervals at a work to rest ratio of 1:1 for 2 minutes then ran to exhaustion. Three 6-second isometric contractions were conducted for the knee extensors on a custom-built dynamometer chair for the MVC tests (6) and reported as normalized values.

All data are expressed as mean ± standard deviation and were analysed using the Statistical Package for Social Sciences (SPSS, version 18, Chicago, IL). The test-retest reliability using ICC (SPSS two-way mixed, 95% confidence intervals) was examined amongst four female and eight male participants from the current study by conducting two MVC tests across different days, but at the same time of day. The ICC values were considered high above 0.9; moderate above 0.8 and below 0.9; and questionable below 0.8 (20). The measurement error was ascertained by quantifying the intra-individual CV with associated 95% confidence interval (12). The WD in knee extensor torque were determined based on a nomogram for the estimation of the measurement repeatability error in accordance with the CV (1). Paired t-tests were used to determine differences between the two MVC tests conducted as part of the reliability measure. One-way repeated measures analysis of variance (ANOVA) was used to analyse differences in knee extensor torque (KET) conducted during week 6 for the CT group. A two-way (group x time) repeated measures ANOVA was used to analyse difference in KET during week 6 for the CT group and week 4 for the ST group. Bonferroni's adjustments with pair-wise comparisons were used to determine the location of the difference. The alpha level was set at 0.05. The effect size (ES) (Cohen's *d*) were also calculated for KET between groups and between time points of the MVC tests conducted during week 6 for the CT group and week 4 for the ST group with the magnitudes trivial at d = 0.2, medium at = 0.5, large at = 0.8 and greater than large at = 0.8.

Results

The KET between the two MVC tests conducted as part of the reliability measure were 283.6 ± 83.7Nm and 284.6 ± 73.5Nm, respectively. The ICC was 0.95 (0.82-0.98), the CV was 4.6 (2.3-6.9)% and the WD measured according to the measurement error was 6.9%.

For the CT group, a significant reduction in torque was found when measured prior to the four endurance training sessions during week 6 when compared to baseline ($P < 0.05$; ES = 1.5, 0.9, 1.0 and 1.1, respectively) (Figure 2). However, no significant differences were found in torque across the three days during week 4 for the ST group ($P \geq 0.05$; ES = 0.6 and 0.004, respectively) (Figure 3).

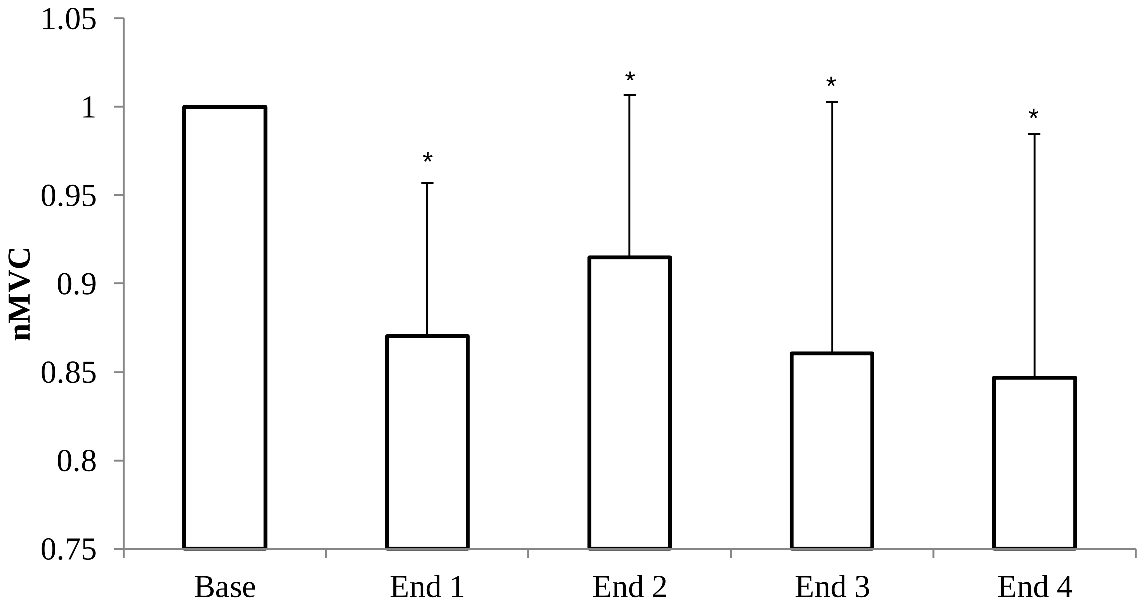

Figure 2. Normalised maximal voluntary contraction (nMVC) measured prior to week 6 as baseline (Base) and prior to the three endurance training sessions (End 1, End 2 and End 3, respectively) during week 6 for the concurrent training group.

* Significantly less than Base (*P* < 0.05)

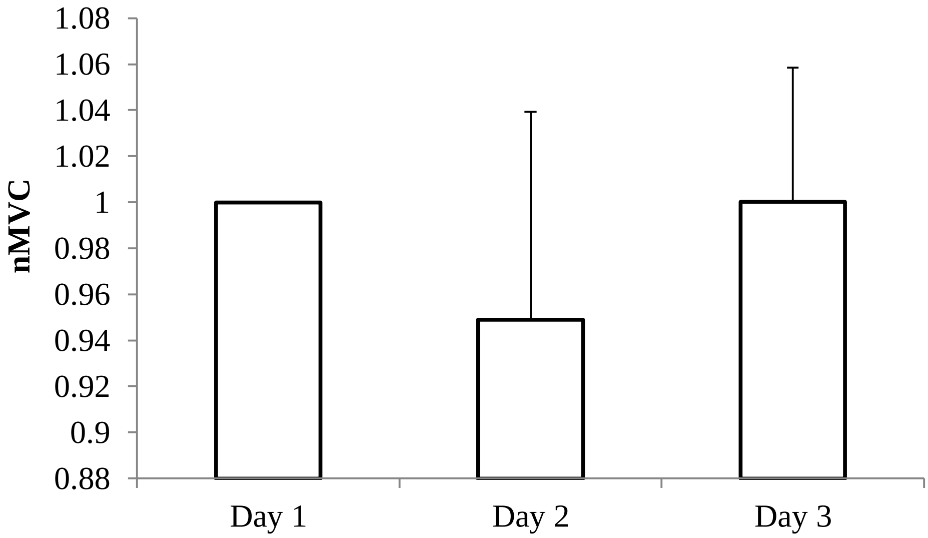

Figure 3. Normalised maximal voluntary contraction (nMVC) measured prior to the strength training sessions on Day 1 and Day 3 and in-between the strength training sessions on Day 2 for the strength training group.

A significant group x time effect was found in torque for the CT and ST groups prior to the strength training sessions (*P* < 0.05). When compared between groups, torque was significantly greater for the CT group compared to the ST group prior to the second strength training session (*P* < 0.05; **ES = 2.1**) (**Figure 4**). In addition, torque was significantly reduced prior to the second strength training session when compared to that measured prior to the first strength training session for the CT group ($P < 0.05$; ES = 1.6) although no differences were found for the ST group ($P \geq 0.05$; ES = 0.004) (Figure 4).

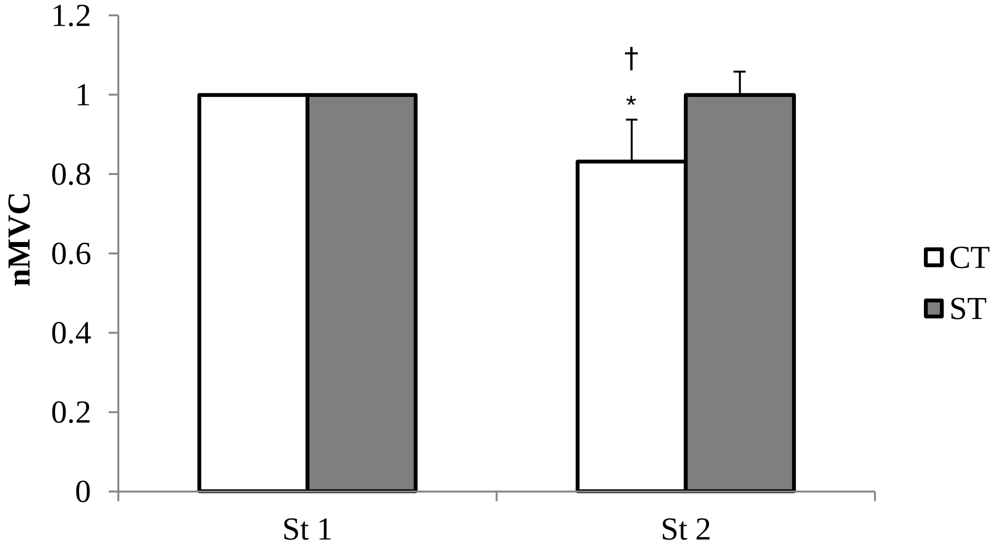

Figure 4. Normalised maximal voluntary contraction (nMVC) measured prior to the two strength training sessions (St 1 and St 2, respectively) during week 6 for the concurrent training group (CT) and during week 4 for the strength training group (ST).

* Significantly less than the St 1 session ($P < 0.01$)

† Significantly less than the ST group ($P < 0.01$)

Discussion and Conclusion

According to KET measured across two days amongst four female and eight male participants, the ICC and CV were 0.95 (0.82-0.98) and 4.6 (2.3-6.9)%, respectively. These results suggest high repeatability and minimal intra-individual variability. Further, the WD was 6.9%, indicating that an approximate 7% difference in KET as a result of a particular intervention is meaningful, despite differences in gender, and is less that that reported by a previous study amongst a group of trained and moderately trained male runners during an identical MVC protocol (6). Subsequently, it is reasonable to suggest that confounding effects as a result of combining male and female participants were limited. In addition, the nature of such sample in the current study would allow the findings to be applied to a wider demographic.

When examining KET during the experimental trials, results showed that KET was significantly reduced prior to both strength and endurance training sessions when combining high intensity strength training sessions on alternating days with moderate to high intensity endurance training sessions on consecutive days. Furthermore, when comparing KET measured at baseline to that measured prior to the four endurance training sessions and the second strength training session for the CT group, the effect size was greater than large (i.e. > 0.8). Subsequently, it appears that moderately endurance trained males and females may experience neuromuscular fatigue as result of concurrent training when prescribing each mode of training sessions similar to the current study. However, strength training sessions alone did not have an impact on MFGC, accepting the hypothesis.

The attenuation in MFGC for the CT group prior to both strength and endurance training sessions following the first strength training session suggests that the morphological properties of the lower extremity muscles did not recover with the CT training protocol incorporated in the current study. Whilst the current study appears to be the first to examine the acute effects of performing strength and endurance training sessions over multiple days, previous studies have reported attenuation in MFGC for up to 48 hours following strength training (17) and up to 6 hours following endurance training (3). The reduction in MFGC as a result of strenuous exercises has been associated with muscle glycogen depletion (16), muscle damage (18), delayed onset of muscle soreness (13) and neuromuscular fatigue (9).

For the ST group, when comparing KET measured prior to the first and second strength training sessions (i.e. the first and third day), no significant differences were found. Furthermore, the ES was 0.004, indicating that the magnitude of reduction in KET was trivial. These results suggest that the knee extensor muscles regained function to produce optimum force with a 48-hour recovery period. However, whilst no significant differences were found 24 hours following the first strength training session (i.e. the second day) for the ST group, there was an approximate 5% reduction which is in proximity to the WD found as a result of the reliability measure in the current study. Furthermore, the magnitude of KET reduction was medium with an ES of 0.6, suggesting that the neuromuscular properties of the knee extensors may experience deleterious effects 24 hours following high intensity lower extremity strength training. When compared between groups, significant differences were found in KET between the CT group and ST group when measured prior to the second strength training session. This provides further indication that moderate to high intensity endurance training sessions may extend the duration of fatigue induced by high intensity lower extremity strength training.

In light of the above, the inability to produce optimum muscular force tends to suggest that the quality of training sessions would be compromised as exercises would not be performed at desired levels (15). Subsequently, insufficient recovery periods between each mode of training session may cause an accumulation effect of fatigue over the entire CT training program, which would impair training stimuli for optimal adaptation (3).

Practical application

The findings from the current study showed that MFGC was reduced when combining high intensity lower extremity strength training sessions on alternating days and moderate to high intensity endurance training sessions on consecutive days. In order to alleviate possible carry-over effects of fatigue between each mode of training session, it is advised to prescribe strenuous strength and endurance training sessions on alternating days. Alternatively, the intensity of endurance training sessions could be adjusted to limit the extent of fatigue. The current study also showed that MFGC returned to baseline with 48 hours of recovery although KET was reduced by approximately 5% with the magnitude of the difference considered to be moderate. Subsequently, high intensity lower extremity strength training sessions similar to that prescribed in the current study could be undertaken with 48 hours of recovery upon completion of habituation, although caution should be taken with 24 hours of recovery.

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Appendix 2 – Permission for print

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