**Bond University**

**DOCTORAL THESIS**

# Biomechanical analyses of strongman exercises using inertial motion capture methods.

Hindle, Benjamin

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# Biomechanical analyses of strongman exercises using inertial motion capture methods

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# ABSTRACT

Strongman is a strength-based sport where athletes compete to set personal bests and determine the strongest competitor. Unlike powerlifting and weightlifting, strongman requires athletes to lift, carry and pull heavy (and often large) objects, testing the athlete under a wide variety of loading conditions.

The aim of the PhD thesis was to develop, validate and use ecologically valid motion capture methods to describe the biomechanics of experienced male and female strongman athletes undertaking previously under-assessed strongman exercises, to better inform the practices of strongman coaches and athletes and strength and conditioning coaches.

From two systematic reviews (Chapter 2, Chapter 3), the yoke walk and atlas stone lift were identified as the most under-researched exercises commonly trained by strongman athletes. Limitations associated with traditional motion capture methods were suggested to partially explain the lack of biomechanical analyses performed on these exercises.

Inertial motion capture (IMC) was presented as a solution to overcome many of the limitations of traditional motion capture methods. A technical summary (Chapter 5) of IMC data processing methods was used to develop an IMC approach suitable for the biomechanical analysis of strongman exercises.

The validity of the devised IMC approach was assessed against an optical motion capture (OMC) system while participants performed the squat, box squat, sandbag pickup, shuffle walk and bear craw (Chapter 6). Good to unacceptable agreement with the OMC system was recorded for lower limb kinematic measures across all exercises, while good to excellent agreement was reported for spatiotemporal measures during the shuffle walk and bear crawl.

The biomechanics of the yoke walk were characterised by: flexion of the hip and slight to neutral flexion of the knee at heel strike; slight to neutral extension of the hip and flexion of the knee at toe-off; and moderate hip and knee ROM (Chapter 7). During the acceleration phase, athletes used an abbreviated gait pattern to increase their stride rate. No main effect between-sex biomechanical differences were observed and few two-way interactions between sex and interval were observed.

The biomechanics of the atlas stone lift were characterised by a recovery, initial grip, first pull, lap and second pull phase (Chapter 8). The initial repetitions in a series of four stones of increasing mass, were abbreviated versions of the later repetitions, which corresponded to a reduction in phase and total repetition duration. Between-sex biomechanical differences were primarily observed at the hip and were attributed to anthropometric differences in male and female athletes.

As a result of this thesis, strongman coaches and strength and conditioning coaches will be better equipped with an understanding of the yoke walk and atlas stone lift required to: provide strongman athletes with recommendation on how to perform these exercises based on the technique used by experienced strongman athletes; conceptualise technique improvements for performance enhancement and injury minimisation; and prescribe the use of these exercises as a training tool for both strongman and non-strongman athletes. Researchers will be able to better direct future research into the biomechanics of strongman exercises and the development of IMC.

## KEY WORDS

Biomechanics, motion capture, inertial measurement, IMU, wearables, strength-sports, weightlifting, powerlifting, strongman.

## Declaration By Author

This thesis is submitted to Bond University in fulfilment of the requirements of the degree of Doctor of Philosophy by Research.

I declare that the research presented within this thesis is a product of my own original ideas and work and contains no material which has previously been submitted for a degree at this university or any other institution, except where due acknowledgement has been made.

Name: Benjamin Richard Hindle

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Date: 26 / 04 / 2021

## DECLARATION BY CO-AUTHORS

Paper 1: The biomechanics and applications of strongman exercises: a systematic review.

| Authors | Study design | Data collection | Data analysis | Manuscript drafting | Proofing |
|---|---|---|---|---|---|
| Benjamin Hindle | 40 | 100 | 85 | 100 | 10 |
| Anna Lorimer | 20 | - | 5 | - | 30 |
| Paul Winwood | 10 | - | 5 | - | 30 |
| Justin Keogh | 30 | - | 5 | - | 30 |

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## Research Outputs

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Hindle, B. R.; Lorimer, A.; Winwood, P.; Keogh, J. W. The biomechanics and applications of strongman exercises: A systematic review. Sports Medicine - Open 2019, 5, 49, doi:10.1186/s40798-020-0239-3.

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Hindle, B. R.; Lorimer, A.; Winwood, P.; Brimm, D.; Keogh, J. W. L. The biomechanical characteristics of the strongman yoke walk. Frontiers in Sports Active Living 2021, 3, 670297, doi: 10.3389/fspor.2021.670297.

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## Ethics Declaration

The research associated with this thesis received ethics approval from the Bond University Human Research Ethics Committee. Ethics application numbers:

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## Copyright Declaration

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# CONTENTS

## LIST OF TABLES

## List of Figures

# List of Abbreviations

| | |
|---|---|
| 1RM | One repetition maximum |
| 2D | Two-dimensional |
| 3D | Three-dimensional |
| 6RM | Six repetition maximum |
| AHRS | Attitude heading reference system |
| AMRAP | As many repetitions as possible |
| CEA | Common everyday activities |
| COM | Centre of mass |
| DCM | Direction cosine matrix |
| DEF | Default |
| DM | Distribution model |
| EMG | Electromyography |
| ES | Effect size |
| FC | Final contact |
| FUNC | Functional calibration |
| HAB | Hip abductor |
| HP | High performing |
| IC | Initial contact |
| IMC | Inertial motion capture |
| IMU | Inertial measurement unit |
| IR | Infrared |
| LoA | Limits of agreement |
| LP | Low performing |
| MAPE | Mean absolute percentage error |
| MARG | Magnetic angular rate and gravity |
| MVC | Maximal voluntary contraction |
| OMC | Optical motion capture |
| PRISMA | Preferred reporting items for systematic reviews |
| RMSE | Root mean square error |
| ROM | Range of motion |
| SFO | Single frame optimisation |
| STA | Soft tissue artifacts |
| STAT | Static calibration |
| TAF | Tuned and filtered |
| TWTE | Traditional weight training exercises |
| VMC | Video motion capture |
| ZUPT | Zero-velocity update |

# CHAPTER 1:

# INTRODUCTION

# 1. Introduction

Strongman is a strength-based sport, similar to weightlifting and powerlifting, in which competitors strive to set personal bests and gain places in competitions by lifting the heaviest load. It is suggested that the roots of strongman date back to the times of the ancient Greek and Egyptian wrestlers, where men would train by lifting heavy stones to gain the strength and endurance required to defeat their opponent [1]. Historians believe a similar form of competitive testing of strength was practiced in Scotland during the twelfth century where clansmen would undertake running, jumping, lifting and wrestling tasks, with the winner being awarded post runner or bodyguard to the king [2]. Today, the traditional strength tasks performed by the Scottish have developed into the Highland Games and now include heavy lifting and throwing events [3]. The modern-day sport of strongman is a combination of: the strength training methods used by ancient Greeks and Egyptians; the Scottish Highland Games; and the modern-day sports of weightlifting and powerlifting.

Strongman exercises include derivatives of the clean and press, deadlift and squat, and often require athletes to lift or carry heavy and awkward objects as quickly as possible over a set distance [4]. Unlike the modern sports of weightlifting and powerlifting, which primarily consist of vertical and bilateral loading, many strongman exercises require horizontal load displacement and include phases of unilateral loading [5, 6]. The most common strongman exercises are described below, with a visual representation of each exercise provided in Figure 1.1.

*Atlas stone lift:* Athletes are required to lift a large stone (either spherical or "naturally" shaped), over a bar, on to a platform or to the shoulder.

*Axle clean and press*: Athletes perform a clean and press using a barbell-like implement, usually of greater thickness than a regular Olympic barbell.

*Axle deadlift:* Athletes perform a deadlift with a barbell-like implement, usually of greater thickness than a regular Olympic barbell, starting from a bar-to-ground clearance of approximately 0.46 m (18").

*Farmers walk:* Athletes carry an independent, loaded frame in each hand for a specified or maximum distance, similar to how one would carry a suitcase.

*Log lift:* Athletes clean and press a large, log-shaped implement over their head.

*Tyre flip:* Athletes flip a tyre end-over-end for a number of repetitions or over a specified or maximum distance.

*Vehicle/sled pull:* Athletes pull a vehicle, either by means of chest harness and moving forward, or in a static position pulling the vehicle by means of a rope in an arm-over-arm motion toward them.

*Yoke walk:* Athletes carry a large, loaded frame, positioned across the rear of their shoulders a specified or maximum distance.


Figure 1.1 a) atlas stone lift; b) axle clean and press; c) axle deadlift; d) farmers walk; e) log lift; f) vehicle pull; g) vehicle pull (arm over arm); h) tyre flip; i) yoke walk. Images reproduced with permission from respective copyright owners.

Since its inception in 1977 with "The World's Strongest Man" competition, the sport of strongman has continued to grow in popularity, with the recent inclusion of competition categories for athletes of varying age, body mass, sex and competition experience. Many strength and conditioning coaches are prescribing strongman exercises to non-strongman athletes [7]. The rapid increase in popularity of the sport of strongman, has created a need for a greater evidence base on how to execute strongman exercises with a biomechanical technique that promotes the greatest performance outcome while reducing some of the risk of injury.

## 1.1 THE STUDY OF BIOMECHANICS

Sports biomechanics uses the fundamental concepts of physics, primarily in the form of Newtons Laws of Motion, and applies them to the human body to assess the forces acting on and within the body, and the resultant motion [8]. The two primary goals of such analysis are to understand injury pertaining to a particular movement pattern, and to improve performance of a movement [8].

Biomechanical analysis undertaken for the purpose of performance improvement and/or injury prevention aims to ensure a mechanically efficient technique is executed by the athlete whilst minimising loading on internal structures [8]. In strongman exercises, a mechanically efficient technique allows an athlete to lift heavier loads for an equivalent muscle force. Manipulation of limb and load positioning, joint range of motion and the manner in which the joints and muscles are coordinated all contribute to the efficiency of the movement [9].

The most basic biomechanical analyses are kinematic and spatiotemporal characterisation, which describe the linear or angular motion of a body in time [10]. Kinematic and spatiotemporal measures are used to describe 'what' is happening to the body throughout a movement, whereas kinetics describes 'why' the body is moving in a particular way [10]. An accurate and comprehensive kinetic analysis involves the measurement of force and anthropometric parameters, and a set of modelling assumptions [11]. While kinetics is an important and valid area of research, describing the general movement pattern through spatiotemporal and kinematic characteristics is typically the first step which must be taken when conducting biomechanics research of an under-researched human movement [11].

## 1.2 ATHLETIC PERFORMANCE AND INJURY RISK

Athletic performance in strongman may be measured in a variety of ways depending on the exercise being undertaken and the schedule of the competition or training session [12]. The most common measures of performance are:

1) an athlete's ability to perform as many repetitions as possible (AMRAP) of a specified load in a set period of time;

2) an athlete's ability to lift a maximum load for a single repetition (1RM);

3) an athlete's ability to carry or pull a given load a specified distance in the shortest time; and

4) an athlete's ability to carry or pull a given load a maximum distance in a set time.

When compared to other strength-based sports such as bodybuilding, powerlifting and weightlifting; Highland Games and strongman have been suggested to have the highest rates of injury [13]. Strongman exercises such as the atlas stone lift and yoke walk have been reported to cause the greatest prevalence of injury in strongman athletes, with the lower back, shoulder, knee and the bicep being the most common sites of injury [14]. When compared with factors such as overtraining/overuse, insufficient warm up, the presence of pre-existing injuries, fatigue and overloading; the greatest contributor to injury during strongman training or competition, as reported by strongman athletes, is poor technique execution [14].

## 1.3 BIOMECHANICAL MEASUREMENT METHODOLOGIES

The biomechanics of a movement may be established using a variety of motion capture methods. Traditionally, three-dimensional (3D) optical, two-dimensional (2D) video and electromagnetic motion capture have been used for the measurement of spatiotemporal and kinematic parameters [15]. For many sporting applications, these methods have limitations [15].

Three-dimensional optical motion capture (OMC) systems consist of a network of infrared (IR) emitting cameras (typically 4 – 30 cameras depending on the size of the capture volume), a series of IR reflective markers attached to specific locations on the body (as many as 50 markers) and a computer to control the network of cameras and record captured data [16, 17]. Optical motion capture has been used widely across sports including baseball [18], golf [19], tennis [20], badminton [21], powerlifting [22] and running [23]. Although 3D OMC is often considered the gold standard of motion capture methods, 3D OMC systems are typically expensive, confined to a small capture volume within a laboratory environment and requires a line of sight to each marker be maintained by at least two cameras within the network to ensure accurate reconstruction of the movement [16, 24]. The occlusion and dislodgement of markers during sporting movements, particularly where large implements are lifted along the surface of the body (as is common in strongman exercises), present a major limitation to this method of measuring spatiotemporal and kinematic parameters.

The method of 2D video motion capture (VMC) requires a single video camera of sufficient capture rate (for the given movement velocity and duration) and freely available computer software to digitise spatiotemporal and kinematic parameters, making it a significantly cheaper alternative to 3D OMC [25, 26]. Two-dimensional VMC is often considered a more practical approach for "in field" biomechanical data collection than 3D OMC and has been used for the analysis of such sports and movements as bicycle motocross (BMX) [26], body-weight squats [27], running [28], strongman [5, 29-32] and gymnastics [33]. Parallax error, when the participant performs a movement at a non-perpendicular angle to the camera, and perspective error, when the participant performs a movement at a distance closer to or further away from the camera than the calibrated capture plane, can cause significant error in spatiotemporal and kinematic measures [34]. Whether a traditional marker-based or marker-less 2D VMC approach is adopted, a line of sight with key anatomical landmarks or limbs must be maintained throughout the entirety of the movement. Similar to 3D OMC, the requirement to have a line of sight to each marker makes 2D VMC impractical when large implements are being lifted or moved along the surface of the body throughout a given movement [16].

Electromagnetic motion capture systems consist of a specially designed suit of electromagnetic receiver sensors which are used to measure 3D position and orientation of the segment to which they are attached with respect to a base station electromagnetic transmitter [35]. Although not as common as 3D OMC and 2D VMC, electromagnetic motion capture has been used in sports including strongman [36], rowing [37], softball [38] and running [39]. Unlike 3D OMC and 2D VMC, electromagnetic motion capture does not rely on line of sight and therefore does not encounter many of the major limitations of optical-based methods when using large implements in a motion analysis [15]. Electromagnetic motion capture is, however, susceptible to errors caused by electromagnetic interference within the environment [15, 17, 40], with laboratory equipment, building structural components and any metallic implements used within the motion analysis being potential sources of electromagnetic interference. Additionally, sampling rates for electromagnetic motion capture are generally low (10 – 1000 Hz) when compared to methods such as 3D OMC (50 – 2000 Hz), limiting the relative accuracy of the analysis of human movement [15].

Recently, inertial measurement unit (IMU) and magnetic, angular rate and gravity (MARG) sensor technologies have been suggested as a practical alternative to overcome many of the limitations of traditional motion capture methods [41]. Inertial motion capture (IMC) relies on a series of IMU/MARG sensors attached to the limbs of a participant to estimate segment location in space. Inertial measurement units consist of an accelerometer and gyroscope to measure linear acceleration and angular rate, respectively, while MARG devices also include a magnetometer to measure magnetic field strength [41, 42]. Measures of linear acceleration, angular rate and magnetic field strength are fused together to estimate the position and orientation of the device (and segment to which the device is attached). One of the major advantages to IMC over traditional methodologies is the ability to estimate spatiotemporal and kinematic parameters whilst "in the field" and not rely on a line of sight to each sensor. As a result of this versatility, IMC has been used in a variety of sports including football kicking [43], snow ski racing [44], cricket [45], swimming [46] and field events such as discus

[47]. Inertial motion capture does come with its own challenges. Complex data processing techniques and algorithms must be used to overcome errors caused by integration of raw sensor measures and magnetic disturbances within the environment. The data processing methodologies may be developed and implemented by the user or purchased at relatively high cost in the form of an "out of the box" commercial IMC system.

Strongman exercises such as the farmers walk and yoke walk are typically performed over a distance of 20 m. Laboratory constraints (e.g., room dimensions) and limited equipment (e.g., number of OMC cameras) may restrict analyses to a portion of typical training or competition distance. The selection of appropriate measurement methods and ecologically valid experimental conditions representing common training or competition environments, loads and event durations are required if data is reflective of normal movement.

## 1.4 Practical applications

Coaches gain knowledge in their chosen sport through a variety of mediums including university degrees, sport specific training courses, personal experience, conversing with other coaches and scientific literature [48]. Traditionally, the primary role of a strength-based sport coach (including strongman coach) is to identify potential issues with an athlete's technique and prescribe appropriate strength and/or technical interventions to enhance performance and minimise risk of injury [49].

In the current research project, the researcher worked with professional strongman and international/national level coach Jean-Stephen Coraboeuf and international/national level strongman coaches Colin Webb and Greg Nuckols to devise research protocols for each strongman experimental study. The collaboration with high calibre strongman coaches and athletes assisted in ensuring maximal practical applicability of the research findings to strongman coaches and athletes.

A description of the biomechanics of under-researched strongman exercises using set, repetition and loading schemes that would be typically performed by athletes in training, provides strongman coaches, athletes and strength and conditioning coaches with the information required to:

- provide male and female strongman athletes with recommendation on how to perform the selected strongman exercises based on the common techniques of experienced strongman athletes;
- conceptualise technique improvements for performance enhancement;
- identify possible injury risks associated with performing the selected strongman exercises; and
- prescribe the use of the selected strongman exercises as a training tool for both strongman and non-strongman athletes.

By establishing a practical means of collecting ecologically valid biomechanical data in an "in field" setting using functional fitness exercises and strongman exercises, researchers will be presented with the opportunity to analyse and gain a greater understanding of previously under-researched movements.

Throughout this thesis the term 'functional fitness exercises' will be used to describe variations of strongman exercises which may be performed by persons at lighter loads or with similar implements (although not strictly replicable) to those used in strongman training or competition. Many strongman exercises, including the farmers walk, atlas stone lift and sandbag loading, resemble common activities of daily living, albeit performed at a much greater load. Performing such exercises at lighter load, using similar implements, may be expected to see benefit in improving one's ability to perform everyday activities such as picking up and moving heavy/awkward objects, thus, improving one's functional fitness [50].

## 1.5 THESIS OVERVIEW

### 1.5.1 THESIS AIM

The aim of the PhD thesis was to develop, validate and use ecologically valid motion capture methods to describe the biomechanics of experienced male and female strongman athletes undertaking previously under-assessed strongman exercises, to better inform the practices of strongman coaches and athletes and strength and conditioning coaches.

### 1.5.2 GUIDING RESEARCH QUESTIONS

The over-arching aim of this project will be achieved by answering a series of six guiding research questions which were developed throughout the project. An overview of the workflow and guiding research questions developed at each stage of the thesis is presented in Figure 1.2.

The thesis consists of nine chapters in total. Chapter 2 and Chapter 3 provide a systematic review of strongman specific biomechanics research and answer Question 1 and Question 2. Chapter 4 summarises and rationalises the research methodologies used in the experimental studies and provides guidance for Chapter 5. Chapter 5 presents a methodological technical summary literature review and in part answers Question 3. Chapter 6 is a methodological validation study answering the remainder of Question 3. Chapter 7 and Chapter 8 are cross sectional observational experimental studies, answering Question 4, Question 5 and Question 6. Chapter 9 summarises the findings of the project.

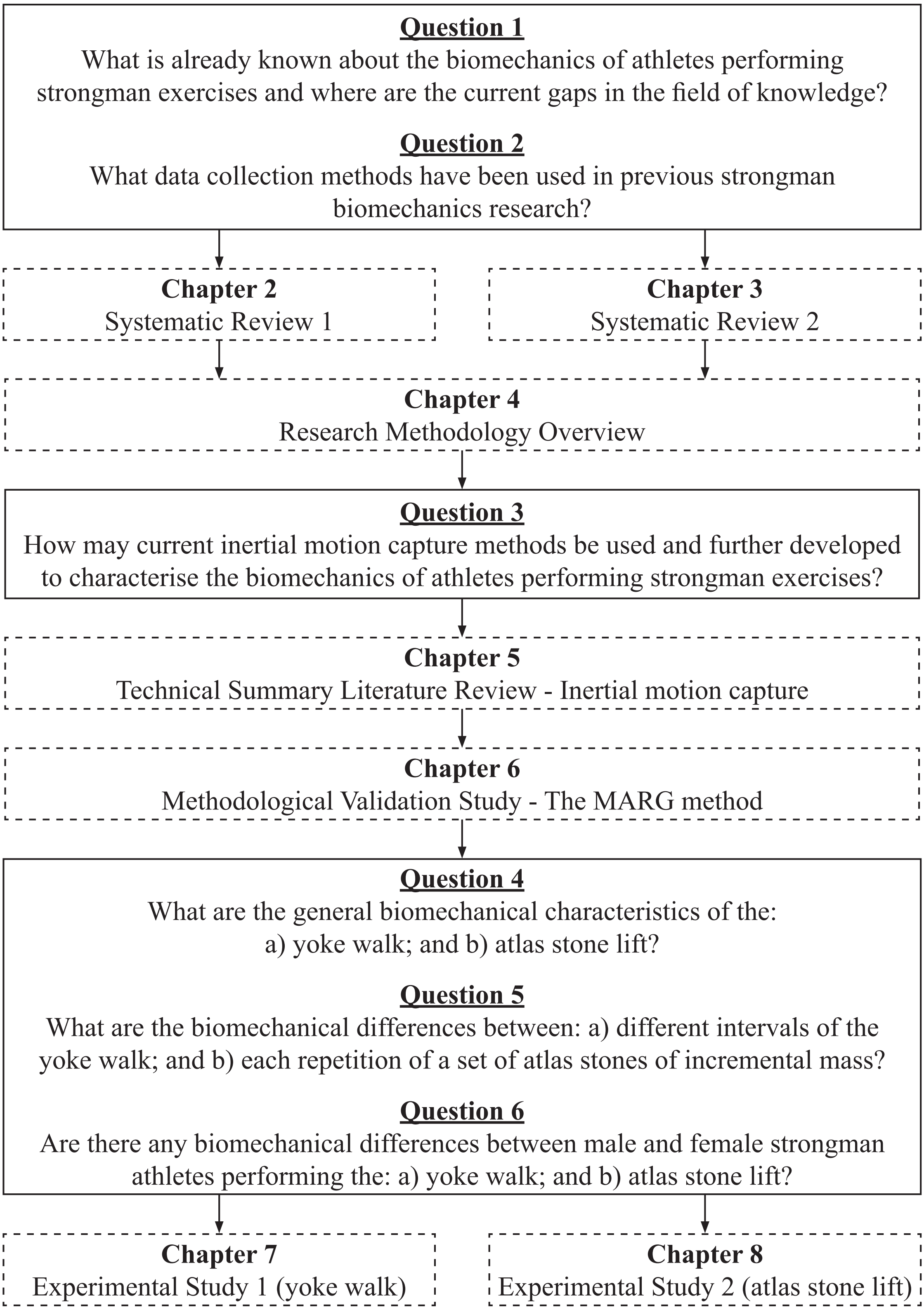


Figure 1.2 Workflow of the thesis.

### 1.5.3 Thesis structure

A single systematic review of the limited biomechanics research was initially conducted to gain insight into where further research was necessary. A second systematic review, building on the initial systematic review was undertaken based on feedback from reviewers during the confirmation of candidature process. One systematic review was conducted to assess the biomechanical research methods used within the existing strongman biomechanics research (Chapter 2), while the second was conducted to assess the results and applications of the current strongman biomechanics research (Chapter 3).

Based on the findings of Chapter 2 and Chapter 3, in combination with discussions held with professional strongman and coach Jean-Stephen Coraboeuf, the yoke walk and atlas stone lift were selected to be the focal strongman exercises of this thesis. With no previous kinematic description of the yolk walk and atlas stone event, it was important to start the biomechanical analysis here, with spatiotemporal and kinematic analysis. Kinetic analyses were beyond the scope of this PhD project.

The challenges associated with the use of traditional methods of collecting spatiotemporal and kinematic measures of athletes performing strongman exercises were highlighted in the systematic review in Chapter 2 and assisted in informing the methods used to collect biomechanical measures in this PhD project. Inertial motion capture was the most appropriate method of data collection to ensure the ecological validity of results.

A set of research methodologies for each of the experimental chapters was devised, detailed in Chapter 4, based on the literature reviews conducted in Chapter 2 and Chapter 3 and discussions held with a panel of strongman coaches. The methodology overview presented in Chapter 4, provided direction for the IMC approach used for the collection of biomechanical data within the PhD project.

A technical summary literature review was conducted to investigate the data processing methods required to develop an IMC methodology suitable for highly dynamic functional fitness exercises, similar to strongman exercises (Chapter 5). The validity of the proposed IMC methodology was measured against the previously validated OMC method for lower limb kinematic and spatiotemporal measures (Chapter 6).

Two cross-sectional observational studies were conducted to describe the biomechanical characteristics of the yoke walk and atlas stone lift (Chapter 7 and Chapter 8, respectively). Emphasis was placed on maintaining a high level of ecological validity in each study design by ensuring data collection under regular training/competition preparation conditions, taking into consideration common loading, set, repetition and rest period practices of strongman athletes. The focus on maintaining ecological validity ensured the generalisability of these results and the relevance of the research to a real-world setting.

Finally, a summary of the findings from the PhD project were presented in Chapter 9. In line with the overall aim of the PhD, the practical applications of the findings are summarised to extend the knowledge and practices of strongman athletes, coaches and strength and conditioning coaches.

It is acknowledged that there is some repetition of figures, explanations and abbreviations throughout the thesis. Whilst every effort has been made to minimise unnecessary repetition, some chapters have been published or submitted for publication and are therefore presented in publication format. With the exception of Chapter 1, each chapter has been written to stand alone, thus minimal reference to preceding or proceeding chapters are made.

#### 1.5.4 SIGNIFICANCE OF THE THESIS

The research presents the first empirical spatiotemporal and kinematic characteristics of the yoke walk and atlas stone lift, and the first scientific research to include female strongman athletes, significantly contributing to the growing body of knowledge on the sport of strongman. The research provides an initial description of the strongman movements, allowing future research into the biomechanical determinants of performance and potential injury risks associated with the exercises. Greater understanding of the biomechanics and physiology of the sport should lead to greater feats of strength, potentially attracting more media attention, and further growing the sport.

As the program of research is the first in the space of strongman biomechanics to include both male and female athletes, attention was given to assessing if any between-sex biomechanical differences exist. While this between-sex assessment adds to the body of research assessing between-sex biomechanical in strength sports, it may also be used by researchers to direct future sex-specific strongman research.

The current program of research further develops and implements modern motion capture methods for the analysis of movements not suitable to traditional motion capture techniques. It is hoped that the current research will encourage further development of IMC for strongman and functional fitness exercises.

# CHAPTER 2:

# SYSTEMATIC REVIEW 1

# 2. A SYSTEMATIC REVIEW OF THE BIOMECHANICAL RESEARCH METHODS USED IN STRONGMAN STUDIES

## 2.1 PREFACE

The systematic literature review component of this thesis was originally a single systematic review. Feedback from the confirmation of candidature process suggested undertaking two separate systematic reviews, to further expand on the similarity between strongman exercises, traditional weight training exercises and common everyday activities. Systematic Review 1 (Chapter 2) contains one less paper than Systematic Review 2 (Chapter 3) due to the different search periods used for each review. The absence of this paper in Systematic Review 1 does not change the conclusions of the review.

The purpose of this chapter was to establish a broad understanding of the previous research on the biomechanics of strongman exercises. The exercises, study populations, testing protocols (sets, repetitions, loads, rest periods), data collection methods and biomechanical measures reported in previous strongman biomechanics research was summarised. This chapter, in conjunction with Chapter 3 assisted in progressing previous research methods to ensure the greatest impact and practical applicability of the strongman biomechanics experimental studies presented in Chapter 7 and Chapter 8. Question 1 *"What is already known about the biomechanics of athletes performing strongman exercises and where are the current gaps in the field of knowledge?"* and Question 2 *"What data collection methods have been used in previous strongman biomechanics research?"* were addressed in this chapter.

Chapter 2 is an Accepted Manuscript version of the below cited article, published by Taylor & Francis Group in Sports Biomechanics on 27 May 2019. This chapter has been reproduced with permission of the publisher, Taylor & Francis, and is available online at: https://doi.org/10.1080/14763141.2019.1598480.

Hindle, B. R.; Lorimer, A.; Winwood, P.; Keogh, J. W. L. A systematic review of the biomechanical research methods used in strongman studies. Sports Biomechanics 2019, 1-30, doi:10.1080/14763141.2019.1598480.

## 2.2 ABSTRACT

As the sport of strongman is becoming increasingly popular, and such exercises are being commonly used by strength and conditioning coaches for a wide range of athletic groups, a greater understanding of the biomechanics of strongman exercises is warranted. To improve the quality of research, this systematic review summarised the research methodology used in biomechanical studies of strongman exercises and identified potential improvements to current approaches. A search of five databases found ten articles adherent to the predefined inclusion criteria. The studies assessed eight strongman exercises and included male participants of relatively similar body mass but varying training backgrounds. Due to the complexity of strongman exercises and the challenges in collecting advanced biomechanical data in the field, most studies used simplified measurement/analysis methods (e.g., 2D motion capture). Future strongman biomechanical studies should: assess under/un-researched strongman exercises; include a greater number of experienced and female strongman athletes; and utilise more advanced (e.g., 3D motion capture and/or inertial sensor) technology so to provide a broader range and greater quality of data. Such approaches will provide strength and conditioning coaches, strongman coaches and athletes with a greater understanding of strongman exercises, thereby further improving exercise prescription, athlete performance and minimising risk of injury.

Key words: Kinematics, kinetics, motion analysis, weightlifting.

## 2.3 INTRODUCTION

Strongman is a competitive strength-based sport consisting of exercises which are typically heavier versions of common activities of daily living, traditional tests of strength or more awkward/challenging variations of traditional weight training exercises such as the squat, deadlift and clean and press [51]. Common strongman exercises utilise equipment such as: stones and loaded frames for lifting and carrying; logs and oversized dumbbells for overhead pressing; tyres for flipping; and vehicles and loaded sleds for pulling [13].

With the increasing popularity of strongman as both a competitive sport and as a source of alternative strength and conditioning training exercises for athletes of wide sporting backgrounds, the quantity and quality of research on the sport of strongman is continuing to increase. This research has examined the training and tapering practices of strongman athletes [3, 52-56], how strength and conditioning coaches utilise strongman implements in their athletes' programmes [7], the physiological responses to strongman training [4, 50, 51, 57-59], and the injury epidemiology of strongman athletes [14]. It should be acknowledged that some of this literature includes narrative reviews and/or opinion pieces on how strongman exercises could be best integrated into strength and conditioning programmes for non-strongman athletes.

Due to the emergent nature of the sport, wide range of exercises that may be performed in competition or training, and the apparent complexity of strongman exercises, it is expected that some level of between study variation may be encountered when attempting to biomechanically analyse strongman exercises. Therefore, the primary objective of undertaking this systematic review was to collect and assess information on the research methods used in existing studies where researchers primarily focus on the biomechanical analysis of a strongman exercise. By addressing this primary objective, the current systematic review will result in a summary of the: exercises, study designs, study populations, and biomechanical analysis methods and measurements utilised in the existing literature. The secondary objective of undertaking this systematic review is to identify the gaps in the research methodology used in strongman biomechanical studies. By identifying these major gaps, suggested improvements may be made to the current research methodology, better equipping future researchers with the knowledge required to conduct more comprehensive studies of greater quality on this sport. Such an approach will produce research which provides greater insight into how strongman exercises may be used in wider strength and conditioning or injury rehabilitation practice, as well as identify key biomechanical performance determinants of these exercises for strongman athletes and coaches.

## 2.4 METHODS

### 2.4.1 REVIEW PROTOCOL

A review protocol for this paper was developed using the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) guidelines on reporting items for a systematic review and the associated PRISMA checklist [60]. This was used in the planning and development of the systematic review to assure the quality of the review process.

### 2.4.2 SEARCH STRATEGY AND INCLUSION CRITERIA

An initial search was conducted using AusportMed, CINAHL, Embase, Medline (Ovid) and SPORTDiscus up to and including 2 July 2018. Due to the lapse in time between the initial search and submission for publication, a second search was conducted up to and including 25 October 2018. As the primary objective of undertaking this systematic review was to identify all strongman articles in which biomechanical analyses were performed, a two-level keyword search using Boolean operators was conducted. The first level of the search used terms associated with strongman exercises, lifts and training methods, while the second level of the search used terms associated with general biomechanical parameters. The full search strategy used for Medline (Ovid) was: (strongman OR strong man.tw OR strong-man.tw OR junkyard OR junk-yard OR junk yard OR log-lift* OR log lift* OR log press* OR log-press* OR yoke-walk OR yoke walk OR yoke-carry OR yoke carry OR super yoke OR super-yoke OR frame lift* OR frame-lift* OR frame carry OR frame-carry OR farmers walk OR farmers carry OR farmer's walk OR farmer's carry OR suitcase carry OR duck walk OR frame carry OR hercules hold OR husafell stone OR tyre flip* OR tyre-flip* OR tyre lift* OR tyre-lift* OR tire-flip* OR tire flip* OR tire lift* OR tire-lift* OR car flip* OR car-flip* OR atlas ston* OR stone lift* OR conans wheel OR conan's wheel OR fingal's fingers OR fingals fingers OR vehicle pull* OR vehicle-pull* OR sled pull* OR sled-pull* OR sled tow* OR sled-tow* OR truck pull* OR truck-pull* OR car pull* OR car-pull* OR chain drag* OR chain-drag* OR rope drag* OR rope-drag* OR sand bag* OR sand-bag* OR sandbag* OR car lift* OR car-lift* OR vehicle lift* OR vehicle-lift* OR truck lift* OR truck-lift* OR arm over arm pull OR arm-over-arm OR keg toss OR keg-toss OR axle press* OR axle-press* OR dumbbell press* OR dumbbell-press*) AND (biomechanic* OR bio-mechanic* OR kinetic* OR kinematic* OR anthropomet* OR emg OR electromyograph* OR imu OR inertial measurement unit OR exp gait/ OR mechanic* OR force OR velocit* OR force-velocity OR time OR exp motion/ OR exp torque/ OR power OR body mass OR angular OR linear OR moment OR moment-angle OR moment angle OR moment-arm OR moment arm OR momentum OR displac* OR equilibrium OR acceler* OR reac* OR joint OR pressure OR inertia* OR work OR energy OR potential OR injur* OR impuls* OR 3D OR motion capture).

In accordance with the intended exhaustive nature of the search strategy, no limitations were initially placed on language, year of publication, or literature source. To provide a systematic review that captures the methodology used when assessing complex strongman type exercises whilst being of value to the widest possible research community (and still adhering the topic of strongman and biomechanics), no restrictions were placed on the age, gender and lifting/athletic training experience of participants within a study. A set of guidelines outlining the inclusion and exclusion criteria was established by the author (Table 2.1).

All articles returned from the five searched databases were imported into online systematic review software Covidence (Veritas Health Innovation, Melbourne, Australia) and distributed to two independent reviewers. The software automatically removed duplicate articles before each reviewer began the title and abstract screening process. Reviewers voted either 'yes', 'no' or 'maybe' to categorise each article's compliance with the pre-defined inclusion criteria. Articles with vote combinations of 'yes'/'yes', 'yes/maybe' or 'maybe'/'maybe' were put aside for full text screening while articles with vote combinations of 'no'/'no' were discarded from further review. Articles not in the native language of the reviewers (English) were returned by the respective database with sufficient translation for screening. Remaining articles after title and abstract screening were then full text screened by reviewers with each reviewer providing a reason for exclusion based on a hierarchical list of reasons. Where reviewers cast conflicting votes (such as 'yes'/'no' or 'maybe'/'no') during title and abstract screening or full text screening, or gave conflicting reasons for exclusion during full text screening, a consensus meeting was held to reach an agreement between both parties. A final scan of the reference list of all included articles was conducted to identify any relevant articles that were not initially found in the database searches. Forward citation tracking using Google Scholar was then employed to find any other articles that may have also been eligible to be included in the review.

Table 2.1 Inclusion and exclusion criteria.

| | Inclusion | Exclusion | |
|---|---|---|---|
| General | | | |
| Article type | Full peer reviewed journal article<br>Grey literature | Recommendation articles<br>Review articles (non-original work) | Editorials<br>Magazine articles |
| Date | No restrictions | | |
| Language | No restrictions | | |
| Participants | | | |
| Age | No restrictions | | |
| Gender | No restrictions | | |
| Lifting/athletic training experience | No restrictions | | |
| Health | All participants must be free from injury at time of testing | Studies of post injury biomechanics/rehabilitation studies | |
| Study protocol | | | |
| Exercises | Articles including strongman exercises commonly seen in strongman competition will be considered for the systematic review.<br>Articles including the following equipment used in substitution for traditional strongman equipment will also be considered.<br>Sled pull - heavy (> body mass of participant). | Unless being used as a comparative measure to any of the exercises listed in the inclusion column, papers with a primary focus on the following exercises will not be considered: squat, deadlift, bench press.<br>Articles including the following equipment used in substitution for traditional strongman equipment will not be included: studies investigating the use of the sled pull as a training technique for sprint performance; chains for pulling/dragging; sandbags for overhead pressing. | |
| Data measurements | Biomechanical parameters to be considered for the inclusion in this systematic review include: anthropometric measures; joint/segment angular kinematics; kinetic measures; linear kinematics; muscular activity; temporal measures. | Articles with primary focus on equipment mechanics related measurement parameters will not be considered for inclusion in the systematic review. These parameters may include: dynamic and static friction between participant or equipment and a surface (i.e., a friction between ground and sled used in a heavy sled pull; or rolling resistance of a vehicle). | |

### 2.4.3 Quality assessment

A risk of bias and quality assessment was undertaken by two independent reviewers. As no standard checklist appeared entirely suitable for the eligible cross-sectional biomechanical studies identified in this review, a checklist was developed by the authors based on systematic reviews including literature of similar study designs [61-68]. Where disagreements in the scoring was apparent between reviewers a consensus meeting was held to establish agreement. An item was scored as one where the article provided sufficient evidence in support of the criteria, and zero where the criteria was not met. A total risk of bias score was calculated for each article and categorised using the methods of Davids, et al. [62], with articles scoring ≥ 67% considered as having a low risk of bias, articles scoring in the range of 34–66% considered as having a satisfactory risk of bias, and articles scoring ≤ 33% considered as having a high risk of bias. Only articles scoring a low or satisfactory risk of bias were included in the review.

### 2.4.4 Data analysis

To address the primary objectives of this systematic review, the data from the included articles were categorised into four main sections: exercises/objectives, study population, study design, and biomechanical analysis.

## 2.5 RESULTS

### 2.5.1 LITERATURE SEARCH

The five databases originally searched on 2 July 2018, yielded 786 titles of which nine were found to be adherent to the inclusion criteria. After identifying another eligible study [69] via a Google Scholar search, a second search of the five databases was performed so to include Renals, et al. [69] (in press) in the review. The updated search on 25 October 2018, resulted in the addition of one article to the systematic review after the original search conducted on 2 July 2018. A flowchart of the screening process undertaken on 25 October 2018 is presented in Figure 2.1.

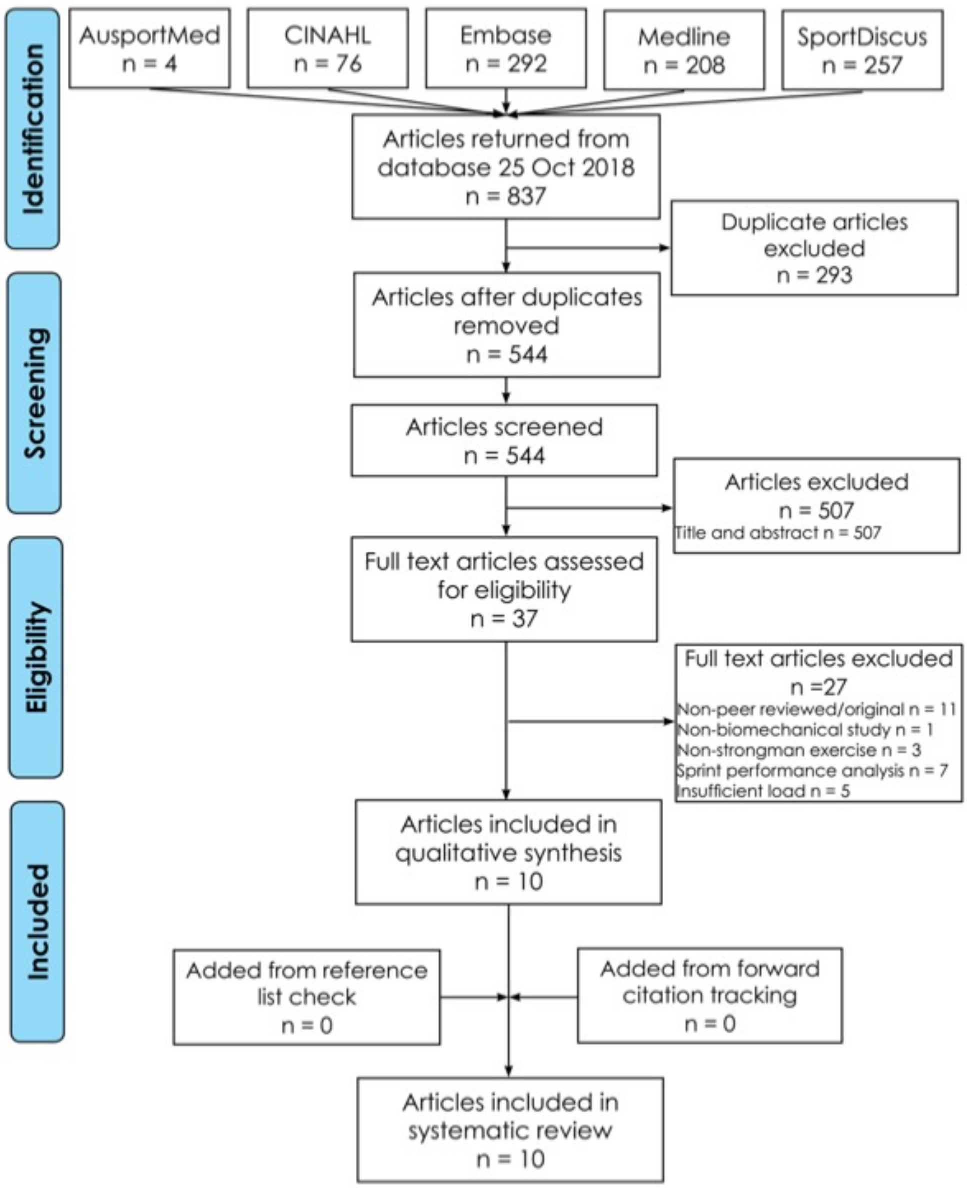


Figure 2.1 Flowchart of screening process undertaken on 25 October 2018.

### 2.5.2 QUALITY ASSESSMENT

Results from the risk of bias assessment are provided in Table 2.2. Generally, the articles reviewed provided a testable hypothesis, used well validated data collection methods, utilised appropriate statistical analysis methods, and presented results which were representative of the tests performed. After conducting the risk of bias assessment on the ten eligible articles, eight were assessed as having a low risk of bias (≥ 67%), while two articles were assessed as having a satisfactory risk of bias (34–66%).

Table 2.2 Quality and risk of bias assessment.

| Article | 1.1 | 1.2 | 1.3 | 2.1 | 2.2 | 2.3 | 2.4 | 3.1 | 3.2 | 3.3 | 3.4 | 4.1 | 4.2 | 4.3 | 4.4 | 4.5 | Score (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Keogh, et al. [29] | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 81 (L) |
| Keogh, et al. [70] | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 69 (L) |
| Keogh, et al. [30] | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 81 (L) |
| McGill, et al. [36] | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 44 (S) |
| Stastny, et al. [71] | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 50 (S) |
| Renals, et al. [69] | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 75 (L) |
| Winwood, et al. [6] | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 69 (L) |
| Winwood, et al. [5] | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 81 (L) |
| Winwood, et al. [32] | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 81 (L) |
| Winwood, et al. [31] | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 75 (L) |

Method for assessing risk of bias: (1.1) study design is clearly stated; (1.2) the objectives/purpose of the study is clearly defined; (1.3) the design of the study adequately tests the hypothesis; (2.1) the criteria for the inclusion of subjects is clearly described; (2.2) the characteristics of the population is clearly described; (2.3) the study sample is representative of the population intended to the study; (2.4) a description of how the study size was arrived at is provided; (3.1) the testing methods are clearly described; (3.2) the measurement tools used are valid and reliable; (3.3) the statistical methods used well described; (3.4) the statistical tests used to analyse the data are appropriate; (4.1) the results are well described; (4.2) the information provided in the paper is sufficient to allow a reader to make an unbiased assessment of the findings of the study; (4.3) confounding factors are identified; (4.4) sponsorships/conflicts of interest are acknowledged; (4.5) any limitations to the study are identified. Note: the risk of bias score for an article (given as a percentage) is calculated through the addition of the score from each criteria being met divided by the maximum possible score across all criteria (16), multiplied by 100. *L* low risk of bias (67–100%), *S* satisfactory risk of bias (34–66%), *H* high risk of bias (0–33%).

### 2.5.3 EXERCISES/OBJECTIVES

The ten eligible articles included in this systematic review have investigated eight different strongman exercises. Although some of the strongman exercises were assessed in multiple articles and multiple strongman exercises were assessed in some articles, the objectives, analysis methods and comparative measures used in many of the articles varied to some degree.

#### 2.5.3.1 *EXERCISES*

The eight strongman exercises biomechanically analysed in the articles reviewed were the atlas stone lift, farmers walk, heavy sled pull, keg walk, log lift, suitcase carry, tyre flip and yoke walk (Figure 2.2).

*Atlas stone lift:* The atlas stone exercise requires the athlete to lift a large, spherical shaped stone off the ground and on to a chest height or higher ledge. In competition the exercise is usually performed as a series of stones of incremental mass which are lifted onto a series of different height ledges, with some competitions also involving the maximum number of repetitions within a minute performed with a stone of constant mass over a bar of constant height [3].

*Farmers walk:* The farmers walk strongman exercise requires the athlete to pick up and move heavy objects carried in each hand. In competition the exercise is most commonly performed over a set distance of between 20 and 50 m, with the athlete striving to complete the distance in the shortest possible time [59].

*Heavy sled/vehicle pull:* The heavy sled/vehicle pull strongman exercise sees the athlete attached to a vehicle (or weight loaded sled) via a chest harness. The heavy sled pull variation is not often seen in competition, rather more commonly used as a training tool to simulate the competition vehicle pull. In both the heavy sled and vehicle pull, the athlete is most commonly required to pull the load a defined distance (often 20–25 m) in the shortest possible time [3, 59].

*Keg walk:* The keg walk requires the athlete to carry a loaded keg on one of their shoulders. In this event, athletes are typically required to either transport a maximum number of kegs from one location to another in a defined period of time, or transport a defined number of kegs in the shortest possible time [72].

*Log lift:* The log lift strongman exercise requires the athlete to lift a metal or wooden log from the ground and then push/press the implement above their head. In competition the exercise is either performed as a maximal load for a single repetition, or a submaximal load for a maximum number of repetitions in a defined period of time (often 60 seconds) [3, 72].

*Suitcase carry:* The suitcase carry requires the athlete to carry a loaded weight in one hand. In competition the exercise is typically performed for a defined distance in the shortest possible time [72].

*Tyre flip:* The tyre flip strongman exercise requires the athlete to repeatedly flip a tractor tyre end over end. In competition this is typically performed over a defined distance, or for a defined number of repetitions in the shortest possible time [3, 70].

*Yoke walk:* The yoke walk requires the athlete to carry a loaded frame balanced across their shoulders. In competition the exercise is either performed as a maximum distance in a defined period of time, or a defined distance in the shortest possible time [72].


Figure 2.2 Illustration of strongman exercises: a) atlas stone lift (Jean-stephen Coraboeuf); b) farmers walk (Jean-stephen Coraboeuf); c) heavy sled/truck pull (Jean-stephen Coraboeuf); d) keg walk (Jean-stephen Coraboeuf); e) log lift (Dione Masters); f) suitcase carry (Jean-stephen Coraboeuf); g) tyre flip (Dione Masters); h) yoke walk (Dione Masters). Images reproduced with permission from respective copyright owners (acknowledged in brackets).

#### 2.5.3.2 *OBJECTIVES*

The earliest article on the biomechanics of strongman exercises was published by McGill, et al. [36] and aimed to use biomechanical parameters to estimate back load, low-back stiffness and hip abduction torque when performing the atlas stone lift, farmers walk, keg walk, log lift, suitcase carry, tyre flip and yoke walk exercises. Keogh, et al. [70] used temporal measurements to determine possible factors which may affect athletic performance of the tyre flip exercise, while similar studies by Keogh and colleagues [29, 30] used both temporal and kinematic measures to determine performance characteristics of the farmers walk and heavy sled pull exercises, respectively. Winwood, et al. [6] sought to quantify the potential relationship between strength performance in weight training exercises and athlete anthropometrics, and strongman competition performance of various strongman exercises including the farmers walk, log lift, tyre flip and truck pull. A series of comparative studies published by Winwood and colleagues compared biomechanical measures of a variety of strongman exercises with those of technically similar traditional resistance training exercises [5, 31, 32]. Most recently, Stastny, et al. [71] conducted a study to determine if muscle strength ratios could be used to predict muscle activation patterns during the farmers walk exercise, and Renals, et al. [69] compared the effect of log diameter on force-time characteristics of the push press phase of the log lift.

### 2.5.4 STUDY POPULATION

The articles reviewed clearly detailed the number, age and body mass of participants included in the study (Table 2.3). Although these variables exhibited some degree of variance between studies, all studies consisted of male participants, with no studies including female participants. Participants included in the articles reviewed typically had at least moderate levels of general resistance training, one repetition maximum (1RM) testing or strongman type functional training experience with many also having a combination of powerlifting and/or strongman competition experience.

Table 2.3 Population of participants.

| Study | Strongman exercise | Number and age of participants | Height (cm) | Body mass (kg) | Training experience (yrs) | | Details of participant training experience |
|---|---|---|---|---|---|---|---|
| | | | | | Strongman | General resist. | |
| Keogh, et al. [29] | Heavy sled pull | Six males 27.0 ± 4.0 yrs | 184.0 ± 6.0 | 101.0 ± 12.0 | NP | NP | All participants were experienced in squats, deadlifts and power cleans with some background in resisted sprint-style sled pulls. |
| Keogh, et al. [70] | Tyre flip | Five males 25.0 ± 7.0 yrs | 180.0 ± 6.0 | 90.0 ± 6.0 | NP | NP | All participants had extensive resistance training experience with four having competed in at least one strongman competition including the tyre flip. |
| Keogh, et al. [30] | Farmers walk | Five males 27.0 ± 4.0 yrs | 176.0 ± 10.0 | 93.0 ± 7.0 | NP | NP | All participants had extensive resistance training experience and were familiar with the squat, deadlift, power clean, push press and bench press. Four of the five subjects had competed in at least one strongman competition including the farmers walk. |
| McGill, et al. [36] | Atlas stone; Farmers walk; Keg walk; Log lift; Suitcase carry; Tyre flip; Yoke walk | Three males 25.0 ± 7.0 yrs | 176.0 ± 10.0 | 117.3 ± 27.5 | NP | NP | All participants were active competitors in strongman competitions with: one competing at international standard; one competing at state standard; one competing at local standard. |
| Stastny, et al. [71] | Farmers walk | Sixteen males 32.5 ± 4.2 yrs | 184.0 ± 6.1 | 89.0 ± 9.2 | NP | NP | All participants had powerlifting competition experience (squat 1RM performance 170.0 ± 35.0 kg). |
| Renals, et al. [69] | Log lift | Ten males 29.8 ± 3.7 yrs | 183.5 ± 6.3 | 116.0 ± 16.9 | 4.45 ± 2.6 | NP | Five participants were of an amateur competitive strongman level. Five participants were of a semi-professional competitive strongman level. |

Table 2.3 continued.

| Study | Strongman exercise | Number and age of participants | Height (cm) | Body mass (kg) | Training experience (yrs) | | Details of participant training experience |
|---|---|---|---|---|---|---|---|
| | | | | | Strongman | General resist. | |
| Winwood, et al. [6] | Farmers walk; Log lift; Tyre flip; Truck pull | Twenty-three males 22.0 ± 2.4 yrs | 184.6 ± 6.5 | 102.6 ± 10.8 | NP | NP | All participants were semi-professional rugby players with extensive strength training experience including 1RM testing and strongman training exercises. |
| Winwood, et al. [5] | Farmers walk | Six males 24.0 ± 3.9 yrs | 181.6 ± 9.4 | 112.9 ± 28.9 | 2.7 ± 1.6 | 6.5 ± 2.7 | All participants were well-trained strongman athletes with extensive experience performing both the traditional and strongman lifts. Four athletes had national strongman competition experience while two had regional strongman competition experience. Pre-requisite of two years of strongman training experience, having competed in at least one strongman competition and be injury free. |
| Winwood, et al. [32] | Heavy sled pull | Six males 24.0 ± 3.9 yrs | 181.6 ± 9.4 | 112.9 ± 28.9 | 2.7 ± 1.6 | 6.5 ± 2.7 | As per Winwood, et al. [5] |
| Winwood, et al. [31] | Log lift | Six males 24.0 ± 3.9 yrs | 181.6 ± 9.4 | 112.9 ± 28.9 | 2.7 ± 1.6 | 6.5 ± 2.7 | As per Winwood, et al. [5] |

Values presented as (mean ± SD) where possible, *1RM* one repetition maximum, *NP* not provided, *SD* standard deviation, *yrs* years.

### 2.5.5 STUDY DESIGN

All articles reviewed were of a cross-sectional observational study design. The general structure of each study design consisted of a warm-up protocol and a test protocol. The warm-up protocol outlined in each study was of a general nature and inferred basic structural consistency for all participants. The test protocol of most studies detailed the number of sets and repetitions of a given exercise, the allocated rest period between sets/bouts of exercise and the prescribed implement load (Table 2.4).

The number of repetitions, sets and the way in which a set was defined varied between many of the articles reviewed. The variation in the definition of a set was generally seen in the studies whereby walking type strongman exercises were assessed. As strongman walking exercises such as the farmers walk, keg walk, heavy sled/vehicle pull, suitcase carry and yoke walk are typically performed once over a specific distance, the distance in which participants were required to perform these exercises during a trial varied between studies. Less variation was however seen in the definition of a set in the studies in which participants were required to perform repetitions of a static lift such as the log lift, stone lift and tyre flip.

Methods used to determine the loading of implements included the use of a constant absolute implement load for all participants [6, 29, 30, 36, 70], a set percentage of a participant's 1RM [5, 31, 32, 69], or an incremental load based on the participant's six repetition maximum (6RM) [71]. These loads were generally established in a familiarisation session held in the week/s prior to the testing session.

Table 2.4 Protocol design.

| Study | Strongman exercise | Warm-up protocol | Sets performed | Repetitions performed | Rest period | Implement load |
|---|---|---|---|---|---|---|
| Keogh, et al. [29] | Heavy sled pull | Gym based warm-up consisting of:<br>5 min of cycling;<br>Several submax sets of front squats, back squats or power cleans (~10 min);<br>2 submax sets of sled pull with loads between 80–120 kg. | 3 sets | 1 × 25 m (fastest time) | 3 min | 171.2 kg (AP) |
| Keogh, et al. [70] | Tyre flip | Submax sets of deadlifts & power cleans (~ 10 min);<br>2–4 reps of the tyre flip performed in sets of 1–2 reps with a moderate rest period between each rep or set | 2 sets | 6 flips (fastest time) | 3 min | 232.0 kg (AP) |
| Keogh, et al. [30] | Farmers walk | ~ 15–20 min of submax deadlifts and farmers walks | 3 sets | 1 × 25 m (fastest time) | 3 min | 90.5 kg / hand (AP) |
| McGill, et al. [36] | Atlas stone<br>Farmers walk;<br>Keg walk;<br>Log lift;<br>Suitcase carry;<br>Tyre flip;<br>Yoke walk | NP | AS: 1 set;<br>FW: 2 sets;<br>KW: 2 sets;<br>LL: 1 set;<br>SC: 2 sets;<br>TF: 1 set;<br>YW: 2 sets | AS: 1 rep to height of 1.1 m;<br>FW: ~ 10 strides;<br>KW: ~ 10 strides;<br>LL: 1 rep;<br>SC: ~ 10 strides;<br>TF: 1 rep;<br>YW: ~ 8 m | NP | AS: 110.0 kg (AP);<br>FW: 75.0 kg / hand (AP);<br>KW: 40.9 kg (AP);<br>LL: 75.6 ± 14.5 kg;<br>SC: 36.9 ± 8 kg;<br>TF: 309.1 kg (AP);<br>YW: 177.3 ± 24.3 kg |
| Stastny, et al. [71] | Farmers walk | 5 min of cycling;<br>Sets of 25 squats in five different foot positions. | 5 sets at varying loads | 8 m | 30–60 s | Incremental load up to 6RM farmers walk |
| Renals, et al. [69] | Log lift | Self-selected dynamic warm-up. | Barbell: 3 sets<br>250mm ø log: 3 sets<br>316mm ø log: 3 sets | 1 rep per set | 1–5 min | 65% barbell push press 1RM |

Table 2.4 continued.

| Study | Strongman exercise | Warm-up protocol | Sets performed | Repetitions performed | Rest period | Implement load |
|---|---|---|---|---|---|---|
| Winwood, et al. [6] | Farmers walk; Log lift; Tyre flip; Truck pull | Standardised low-intensity warm-up consisting of: Dynamic stretching; Light jogging (aerobic training zone ~ 60% HR max); Body weight exercises. | FW: 1 set LL: 1 set TF: 1 set TP: 1 set | FW: Greatest distance in 40 s c̄ 25 m laps, 180° turn at the end of each lap; LL: AMRAP in 60 s; TF: AMRAP in 40 s; TP: Furthest distance in 40 s | ~ 10 min | FW: 58.0 kg / hand (AP); LL: 75.0 kg (AP); TF: 280.0 kg (AP); TP: 2.5 t (AP) |
| Winwood, et al. [5] | Farmers walk | Participant defined warm-up; Two light sets of each lift (< 40% 1RM) for 6–10 reps; Testing at various loads of required exercise. | Two sets starting on the force plate; Two sets starting 3 m behind the force plate | ~ 6 m plus length of force plate. | Up to 5 min | 70% of deadlift 1RM |
| Winwood, et al. [32] | Heavy sled pull | Participant defined warm-up; Two light sets of each lift (< 40% 1RM) for 6–10 reps; Testing at various loads of required exercise. | Two sets starting on the force plate; Two sets starting 2 m behind the force plate | 3 squat reps (prior to sled tow testing). ~ 6 m plus length of force plate. | Up to 5 min | 70% of back squat 1RM |
| Winwood, et al. [31] | Log lift | Participant defined warm-up; Two light sets of each lift (< 40% 1RM) for 6–10 reps; Testing at various loads of exercise. | 1 set | 1 rep | Up to 5 min | 70% of clean and jerk 1RM |

*AMRAP* as many repetitions as possible, *AP* all participants, *AS* atlas stone, *FW* farmers walk, *HR* max maximum heart rate, *KW* keg walk, *LL* log lift, *rep(s)* repetition(s), *NP* not provided, *RM* repetition maximum, *SC* suitcase carry, *submax* submaximal, *TF* tyre flip, *TP* truck pull, *YW* yoke walk, *c̄* with, *ø* diameter.

#### 2.5.6 BIOMECHANICAL ANALYSIS

Within the reviewed articles, biomechanical parameters (Table 2.5) were analysed using a number of different measurement techniques and equipment. The biomechanical parameters seen in the articles reviewed have been categorised and presented for discussion using a deterministic model approach. The deterministic model is based on how the different categories of biomechanical measures may affect the ultimate performance outcome of the exercise (Figure 2.3).

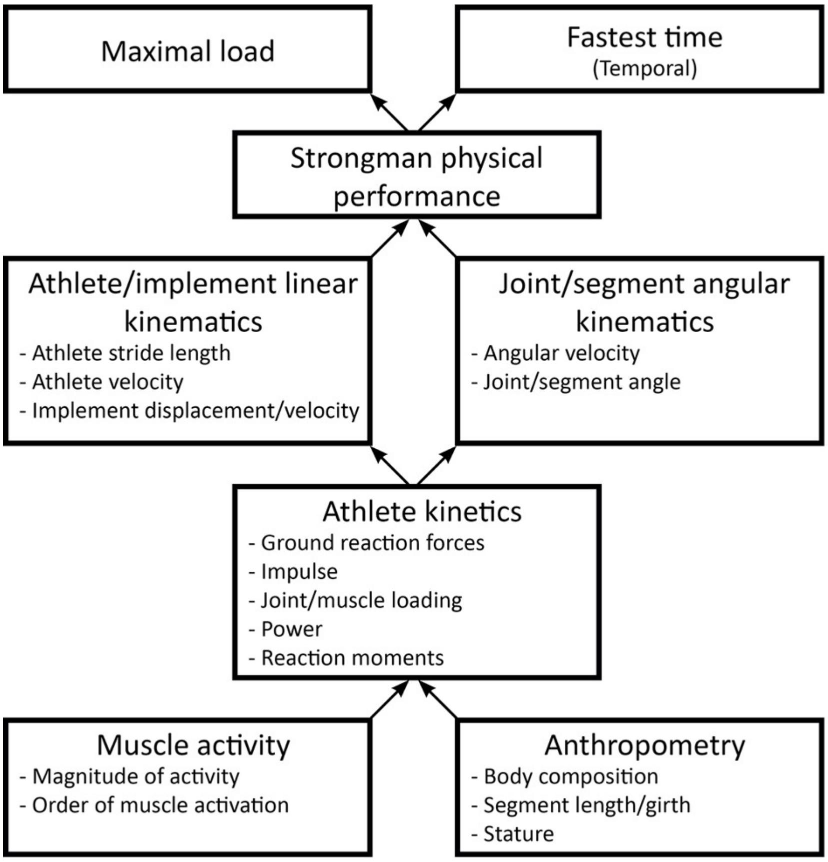


Figure 2.3 Deterministic model of biomechanical parameters.

##### 2.5.6.1 *TEMPORAL MEASURES*

Temporal data of the tyre flip [70], farmers walk [5, 30] and heavy sled pull [29, 32] were collected using a series of cameras to capture two-dimensional (2D) data in the sagittal plane. Computer software was used to post process the video data and record the time taken for the athlete to complete each defined phase of the lift or section/phase of the walk/pull. Temporal data for the fastest and slowest farmers walk, heavy sled pull and tyre flip trials were compared within and between participants in the studies by Keogh and colleagues [29, 30, 70], while Winwood, et al. [5] made group-average temporal data comparisons of the farmers walk to that of an unloaded walk, and Winwood, et al. [32] compared measures between phases of the heavy sled pull. Propulsion phase duration and total lift duration were measured for the log lift push press in Renals, et al. [69], with such measures calculated from force plate data and compared between a barbell and various diameter logs.

#### 2.5.6.2 *ATHLETE/IMPLEMENT LINEAR KINEMATICS*

Athlete linear kinematics were collected for the farmers walk [5, 30] and heavy sled pull [29, 32] by method of marker based tracking using 2D sagittal plane video camera data and post processing computer software. This equipment and methodology was also commonly used to collect joint/segment angular kinematic data as described subsequently. The analysis performed on the athlete/implement kinematic measures for the farmers walk and heavy sled pull were as per the temporal measures presented previously for each respective study [5, 29, 30, 32].

Renals, et al. [69] measured athlete linear kinematics during the log lift push press in the form of vertical velocity and displacement of the athlete's centre of mass. These measurements were calculated by subtracting the body mass of the athlete and the load lifted from the vertical force data leaving the measurement of acceleration, which were then integrated to give vertical velocity and integrated once again to give displacement. These measurements were presented as mean values during the braking and propulsive phases of the lift. Bar/log path trajectory and velocity data in Winwood, et al. [31] were collected by sagittal and frontal plane video recording and processed using computer software. Implement trajectory was plotted as vertical and horizontal displacement as both a function of time and relative to the initial starting point, while velocity data were presented as peak and mean vertical velocity values throughout each phase of the lift.

#### 2.5.6.3 *JOINT/SEGMENT ANGULAR KINEMATICS*

Joint/segment angular kinematic data in the studies by Keogh and colleagues [29, 30], and Winwood and colleagues [5, 31, 32] were collected using 2D video camera data techniques described in the athlete/implement linear kinematics section. The number of markers used to locate and track anatomical locations of the athlete's body ranged from six to 12 with anatomical positioning of these markers varying depending on the exercise being analysed and the biomechanical parameter being assessed. These measures were presented as a range of motion throughout an exercise or an angle at defined instances throughout an exercise.

Lumbar spine angular data were collected in McGill, et al. [36] using a 3Space IsoTRAK electromagnetic tracking system (Polhemus, Inc., Colchester, Vt, USA). The system consisted of a transmitter secured to the pelvis over the sacrum of the participant, and a receiver secured over the T12 spinous process of the participant, allowing for relative position of the lumbar spine to be approximated. In addition, a two video camera system that enabled vision of the frontal and sagittal plane was used to record and synchronise electromyography (EMG) data and spinal posture data obtained from the electromagnetic tracking system. These measures were presented as peak flexion-extension, medial/lateral bend, and twist of the lumbar spine.

#### 2.5.6.4 *ATHLETE KINETICS*

Kinetic measurements within the body of the athlete (in the form of muscle and joint loads) and forces acting externally on the body (in the form of ground reaction forces) were reported in five studies [5, 31, 32, 36, 69]. Muscle and joint force, and torso stiffness estimations in McGill, et al. [36] were derived by first inputting the collected EMG data and spine angular kinematic data into a distribution moment (DM) model [73]. Resultant muscle force and stiffness approximations from the DM model along with spine angular kinematic data were then input into a lumbar spine model based on anatomical approximations to optimise individual muscle force and stiffness. The 18 degree of freedom model utilised an EMG based function to balance the external moment equation of a rigid link model (described subsequently) with the moments produced by the initial muscle and joint force estimations. This method ensured preservation of muscle recruitment patterns seen in the EMG data by adjusting individual muscle force and stiffness coefficients.

Estimations of joint reaction moments about the lumbar spine (L4/L5) were derived in McGill, et al. [36] through the input of digitised spine postural data and anthropometric approximations into a rigid link body model using similar techniques to McGill and Norman [74]. These moments were estimated for flexion/extension, medial/lateral bend and twist. Joint reaction moments of the hip were estimated by first recording a maximum voluntary isometric hip abduction effort for each participant. Kinematic joint angle data in the frontal plane from each of the walking exercises were digitised and input into the rigid link body model to estimate the hip abduction moment experienced throughout each exercise. These results were then normalised to the maximum isometric voluntary hip abduction produced by each participant and expressed as a percentage of the participant's maximum isometric voluntary hip abduction.

Three studies used a Bertec force plate (Model AM6501, Bertec Corp., Columbus, OH, USA) to collect ground reaction force data in the vertical, medial/lateral and anterior/posterior directions [5, 31, 32], while one study used a Kistler force plate (Model 9851B, Kistler Instruments Ltd., Hook, United Kingdom) to collect vertical ground reaction force data [69]. The data were post-processed using computer software and normalised for time, with forces presented in their respective axial directions depending on the exercise and study. Additionally, the log lift studies of Renals, et al. [69] and Winwood, et al. [31] used the ground reaction force data and implement velocity data to estimate power and impulse throughout various phases of the lift.

#### 2.5.6.5 *MUSCULAR ACTIVITY*

Electromyography measurements were collected in McGill, et al. [36] using sixteen electrode pairs placed bilaterally on various abdominal, back and gluteal muscles. Standard EMG practices were generally reported throughout the preparation, collection and processing of the EMG data, with EMG signals full wave rectified and low-pass filtered using a second-order Butterworth filter. These EMG signals were then normalised for each participant to a maximal voluntary contraction (MVC) of each muscle, providing insight into key muscular contributors during various strongman exercises. As detailed previously, these measurements were also used to calculate internal force and stiffness experienced by individual muscle fascicles of the lumbar spine during each exercise.

Stastny, et al. [71] collected EMG data during the farmers walk exercise. A Noraxon Myosystem 1400A (Noraxon, Scottsdale, AZ, USA) EMG system was used to collect raw EMG data from four electrode pairs placed bilaterally on selected hamstring, quadricep and gluteal muscles. Standard EMG practices were generally reported throughout the preparation, collection and processing of the EMG data with data band-pass filtered and smoothed using a root mean square approach. Participants were required to perform MVC at 75° knee flexion/extension and 15° hip abduction on an IsoMed 2000 Dynamometer (D & R Ferstl GmbH, Hemau, Germany) prior to farmers walk testing to establish muscular strength ratios of the hamstring/quadricep, hip abductor/quadricep, and hip abductor/hamstring. Participant EMG data taken during the farmers walk trials were then normalised to MVC testing data and used to determine if a relationship could be established between lower limb muscle strength ratios and muscle activation patterns during the farmers walk.

#### 2.5.6.6 *Athlete Anthropometric Measures*

Athlete anthropometric measures of stature (height), body composition and body segment girths were taken in one of the articles reviewed [6]. Stature measurements were taken using a portable stadiometer (Seca 214, Hangzhou, China), body segment girths were taken using a Lufkin tape measure (Cleveland, OH, USA) and body composition measurements were taken using a bioelectrical impedance machine (InBody230, Biospace, Seoul, Korea). All anthropometric data were collected by a qualified International Society for the Advancement of Kinanthropometry anthropometrist, with the measurements used to determine if a relationship existed between athlete anthropometry and that of maximal strength in traditional weight training exercises, and strongman exercise performance.

Table 2.5 Biomechanical analysis.

| | Keogh, et al. [29] | Keogh, et al. [70] | Keogh, et al. [30] | McGill, et al. [36] | Stastny, et al. [71] | Renals, et al. [69] | Winwood, et al. [6] | Winwood, et al. [5] | Winwood, et al. [32] | Winwood, et al. [31] |
|---|---|---|---|---|---|---|---|---|---|---|
| Exercise | | | | | | | | | | |
| Atlas stone | - | - | - | ✓ | - | - | - | - | - | - |
| Farmers walk | - | - | ✓ | ✓ | ✓ | - | ✓ | ✓ | - | - |
| Heavy sled/vehicle pull | ✓ | - | - | - | - | - | ✓ | - | ✓ | - |
| Keg walk | - | - | - | ✓ | - | - | - | - | - | - |
| Log lift | - | - | - | ✓ | - | ✓ | ✓ | - | - | ✓ |
| Suitcase carry | - | - | - | ✓ | - | - | - | - | - | - |
| Tyre flip | - | ✓ | - | ✓ | - | - | ✓ | - | - | - |
| Yoke walk | - | - | - | ✓ | - | - | - | - | - | - |
| Temporal measures | | | | | | | | | | |
| Ground contact time | ✓ | - | ✓ | - | - | - | - | ✓ | ✓ | - |
| Phase time | | ✓ | - | - | - | Propulsive phase, total lift | - | - | - | - |
| Stride rate | ✓ | - | ✓ | - | - | - | - | ✓ | ✓ | - |
| Swing time | ✓ | - | ✓ | - | - | - | - | ✓ | ✓ | - |
| Linear kinematics | | | | | | | | | | |
| Velocity | Athlete mean | - | Athlete mean | - | - | Propulsive, braking | - | Athlete mean | Athlete mean | Bar vertical |
| Displacement | Stride length | - | Stride length | - | - | Dip depth, propulsive | - | Stride length | Stride length | Dip depth, implement path |

Table 2.5 continued.

| | Keogh, et al. [29] | Keogh, et al. [70] | Keogh, et al. [30] | McGill, et al. [36] | Stastny, et al. [71] | Renals, et al. [69] | Winwood, et al. [6] | Winwood, et al. [5] | Winwood, et al. [32] | Winwood, et al. [31] |
|---|---|---|---|---|---|---|---|---|---|---|
| Angular kinematics | | | | | | | | | | |
| Ankle angle | - | - | ICG-LM-FM | - | - | - | - | LFC-LM-BTM | LFC-LM-BTM | LFC-LM-BTM |
| Knee angle | GT-MTJ-LM | - | GT-ICG-LM | - | - | - | - | GT-LFC-LM | GT-LFC-LM | GT-LFC-LM |
| Hip angle | - | - | - | - | - | - | - | - | AP-GT-LFC | AP-GT-LFC |
| Spinal motion | - | - | - | ✓ | - | - | - | - | - | - |
| Thigh angle | GT-MTJ (VA) | - | GT-ICG (VA) | - | - | - | - | GT-LFC (VA) | - | - |
| Trunk angle | AP-GT (HA) | - | - | - | - | - | - | AP-ASIS (HA) | AP-ASIS (HA) | AP-ASIS (HA) |
| Kinetics | | | | | | | | | | |
| Ground reaction forces | - | - | - | - | - | Vertical: propulsive, braking | - | Tri-axial | Tri-axial | Tri-axial |
| Impulse | - | - | - | - | - | Vertical: propulsive, braking | - | - | - | - |
| Power | - | - | - | - | - | Vertical: propulsive, braking | - | - | - | - |
| Muscle activation | - | - | - | BF, EO, GMA, GME, IO, LD, LES, RA, RF, UES | BF, GME, VL, VM | - | - | - | - | - |
| Muscle/joint kinetics | - | - | - | ✓ | - | - | - | - | - | - |

Table 2.5 continued.

| | Keogh, et al. [29] | Keogh, et al. [70] | Keogh, et al. [30] | McGill, et al. [36] | Stastny, et al. [71] | Renals, et al. [69] | Winwood, et al. [6] | Winwood, et al. [5] | Winwood, et al. [32] | Winwood, et al. [31] |
|---|---|---|---|---|---|---|---|---|---|---|
| Anthropometrics | | | | | | | | | | |
| Body composition | - | - | - | - | - | - | ✓ | - | - | - |
| Segment girth | - | - | - | - | - | - | Calf, chest, gluteal, thigh, upper arm | - | - | - |
| Stature | - | - | - | - | - | - | ✓ | - | - | - |

AP acromion process, ASIC anterior superior iliac crest, ASIS anterior superior iliac spine, BF biceps femoris, BTM base of third metatarsal, EO external oblique, FM fifth metatarsal, GT greater trochanter, GMA gluteus maximus, GME gluteus medius, HA angle taken in reference to horizontal axis, HE heel, HSM head of second metatarsal, ICG inter condylar groove, IO internal oblique, LD latissimus dorsi, LES lumbar erector spinae, LFC lateral femoral condyle, LFE lateral femoral epicondyle, LM lateral malleolus of the ankle, LT lateral thigh, MTJ mid-point of the lateral joint line of the tibiofemoral joint, PSIC posterior superior iliac crest, RA rectus abdominis, RF rectus femoris, TIB tibialis, UES upper erector spinae, VA angle taken in reference to vertical axis, VL vastus lateralis, VM vastus medialis.

## 2.6 Discussion and implications

The methodology used to collect data for the biomechanical analysis of a movement may have significant implications on the quality of the data and its applications to improving athletic performance and/or reducing injury risk. The methodology selected by researchers may be influenced by the exercise being analysed, the study objectives, study population, study design and biomechanical measures desired, with each area discussed in order in the following section. By exploring the methodologies used in biomechanical studies of traditional weight training exercises, future biomechanical studies may produce a higher quality of data, which should result in a more comprehensive understanding of this sport and therefore improve strongman performance and wider strength and conditioning practice.

### 2.6.1 Exercises/objectives

A large portion of the articles reviewed conducted biomechanical analysis on the farmers walk and heavy sled pull exercises [5, 6, 29, 30, 32, 36, 71]. This is possibly due to the common occurrence of these exercises in the strength and conditioning programmes of non-strongman athletes [5]. Although biomechanically assessed in two of the ten articles reviewed, the heavy sled pull exercise is not typically seen in strongman competition, rather it is more commonly used as a training exercise for the vehicle/truck pull seen in competition [59]. The heavy sled pull and the vehicle/truck pull may differ in terms of their performance determinants to some extent due to differences in the frictional behaviour of the two loads. To put a heavy sled in motion, static and dynamic sliding friction must be overcome, with typical coefficients of friction between a heavy sled and an athletic track found to range from 0.3 (static) to 0.47 (dynamic) [75]. When compared to the coefficient of rolling resistance of a vehicle tyre (~0.004) [76], it may be appreciated that in order to overcome the initial inertia of an object of equal mass, a force 75 times greater must be applied to a sled (to overcome static sliding friction) than to a wheel (to overcome the friction apparent as rolling resistance). However, the mass and coefficient of friction are not the only variables that must be considered when assessing the replicability of a heavy sled pull to that of a vehicle pull. A phenomenon known as stick-slip must also be considered. This phenomenon occurs as a result of an object in sliding contact generally having the inability to momentarily continue to move once a propulsive force is no longer applied to the object as would typically be seen with a wheel [75]. As a result of these behavioural differences, the contribution of the current heavy sled pull studies toward improving researcher's understanding of the key biomechanical determinants of the strongman competition vehicle pull is still somewhat unclear.

Although the results from McGill, et al. [36] made reference to some of the biomechanical differences seen between athletes of varying competition standard, the results were not statistically compared. The resultant back load, low-back stiffness and hip abduction torque measurements reported by McGill, et al. [36] were compared between exercises. In a similar fashion, the biomechanical measurements taken in Renals, et al. [69], and Winwood and colleagues [5, 31, 32] were compared between strongman and traditional exercises, with no comparative analysis being undertaken between athletes of varying performance levels. Stastny, et al. [71] also did not measure or compare overall athlete performance, but rather compared muscular activation patterns between athletes of varying muscular strength ratios. The recommendations seen throughout these studies appear to be more directed at strength and conditioning coaches for targeted performance improvements in non-strongman athlete training programmes or for injury rehabilitation/prevention for both strongman and non-strongman athletes.

Contrary to McGill, et al. [36], Renals, et al. [69], Stastny, et al. [71], and Winwood and colleagues [5, 31, 32]; Keogh and colleagues [29, 30, 70] compared biomechanical measures between athletes of varying performance standards. Across these three studies it was found that a number of biomechanical differences exist between athletes of varying performance levels which likely contribute to the overall performance of the athlete. The results from Keogh and colleagues [29, 30, 70] may be of particular value to strongman coaches and athletes wanting to improve competition performance.

Researchers conducting future strongman studies should look to focus on popular strongman exercises with little to no previous research conducted in the field. Such exercises may include the atlas stone lift, single arm dumbbell press, yoke walk and variations of the vehicle pull which are more representative of that seen in strongman competition. Additionally, future studies may consider comparing biomechanical measures between higher and lower performing athletes as has been performed in few studies [29, 30, 70]. Identifying key biomechanical performance determinants of strongman exercises would be expected to improve coaching and the overall performance of strongman athletes at all levels of competition. Information on how to better perform strongman exercises may also be used by special forces, police departments and emergency services personnel who are faced with a life and death situation whereby they are required to move heavy, awkwardly shaped objects and/or carry or drag civilians to safety. Such tasks may be seen to closely replicate some of the exercises undertaken by strongman athletes [30].

### 2.6.2 Study population

The articles reviewed generally consisted of a small sample size (six or fewer participants). Two of the articles reviewed included a larger number of non-strongman athletes ($n$ = 16; $n$ = 23) [6, 71] with backgrounds in other forms of resistance training. Although results from these non-strongman populations may be of relevance to strength and conditioning coaches who are contemplating including strongman exercises into an athlete's training programme, the results from these studies may not be representative of, or generalisable to the competitive strongman athlete population. In addition, the inclusion of non-strongman athletes in some of the studies reviewed likely had a small carry-over effect on subsequent methodology used in the study, such as the warm-up methods and the loads used when performing a given exercise. These considerations will be discussed further in subsequent sections. The small number of competitive strongman athletes included in the articles reviewed may be due to the sport of strongman still being young and the limited number of athletes competing in the sport of strongman in any given geographical location. With the increasing popularity of the sport of strongman it may be expected that future studies will include a greater sample size of national and international level competitive strongman athletes, including female and lighter male participants than have been included in previous studies. Studies of typical strongman athletes would provide results which are of greater relevance to strongman coaches and athletes.

### 2.6.3 Study design

All articles included in the review were of cross-sectional design. This type of study design is commonly utilised in biomechanical research and provides a snapshot of athlete performance and biomechanical parameters at a single point in time. These performance outcomes may be affected by how an athlete is feeling on a particular day and may be influenced by factors such as sleep, stress, nutrition, training load, injury or illness.

No articles published to date have assessed and/or compared biomechanical parameters of an athlete performing a strongman exercise over an extended period of time. While technique in advanced lifters is suggested to remain relatively constant after the initial years of training, metrics of rate of force development and muscular cross-sectional area have been observed to change throughout a single block periodized training cycle in collegiate weightlifters [77]. Researchers undertaking future strongman studies may consider assessing similar biomechanical and anthropometric characteristics and their association with performance at regular intervals throughout the training and competition season of an athlete. The results from such studies may be of particular interest to strongman coaches when programming training blocks for athletes, determining associations between strongman technique, skill acquisition and performance, and also in assessing signs of adaptation, over-training, fatigue and injury. Strength and conditioning coaches may be interested in such longitudinal studies as they would provide greater insight into the benefits and potential injury risks of such exercise programmes.

The way in which implement loading was determined in the articles reviewed exhibited some degree of between study variation. The majority of loads used were somewhat reflective of the experience and/or competitive standard of the athletes tested, with studies that included a greater number of non-strongman athletes typically seeing lighter loading. Many of the articles reviewed lacked detail on the methods used to establish implement load. These details, along with justifications for the use of the method should be reported to provide the reader with a greater context to the study.

Prescribing implement loading based on pre-test 1RM tests could be a useful approach in some studies, as it would provide a way to normalise the data collected based on the participants' muscular strength. This approach has been used in various strength sport biomechanics research such powerlifting [78, 79] and weightlifting [9, 80]. The 1RM based loading approach has been used in four studies where comparisons have been made between strongman and traditional lifts, with the results assisting in improving the understanding of how strongman exercises may be best, if at all, included in the strength and conditioning programmes of non-strongman athletes [5, 31, 32, 69]. However, unlike powerlifting and weightlifting, basing loads on an athlete's 1RM does not mimic actual strongman competition, whereby athletes of a given gender and body mass category compete with the same absolute loads for each exercise (e.g. the same atlas stones, loaded yoke or truck). Utilising such competition loading approach in strongman performance research may be of major interest to strongman coaches and athletes as it provides insight into the most important factors influencing strongman competition performance.

It is also apparent that no strongman biomechanical study to date has assessed an exercise over a range of loads as may be experienced during training and as is standard practice for examining force-velocity-power relationships in traditional resistance training exercises [81-83]. Both strongman coaches and athletes, and strength and conditioning coaches of non-strongman athletes would benefit from such analyses as it may assist in the prescription of loading during a training session or phases of a periodisation training programme where specific performance outcomes are desired.

Limited detail on the warm-up protocol undertaken by participants was provided in articles reviewed. Few articles explicitly stated whether an athlete self-directed or a warm-up routine developed by the researcher was used, making it difficult for the reader to determine the suitability of the methods selected. It could be expected that altering the usual warm-up protocol of an experienced athlete by enforcing a researcher designed warm-up routine may affect the athlete's performance during testing, although evidence supporting or discrediting the use of an athlete self-guided warm up to promote performance across strength sports is lacking. If an intended outcome of a study is to observe the biomechanics of an athlete performing a given exercise in a way that is most representative of how the athlete performs the exercise in training or competition, it would be sensible to replicate regular training practices as much as possible within the testing session, including the athletes' routine warm up protocol.

Researchers undertaking future studies should provide greater detail on the warm-up protocol used, and where experienced strongman athletes are included should use an athlete self-directed warm-up routine, with all warm-up elements documented by the supervising researchers. Researchers interested in strongman performance may consider comparing the effects of different warm-up approaches (including the potential use of post-activation potentiation) on performance in simulated strongman competitions to determine what may constitute optimal warm-up strategies for the sport.

### 2.6.4 Biomechanical analysis

The majority of the articles reviewed used 2D kinematic analysis to estimate sagittal plane temporal measures, athlete linear kinematics and joint/segment angles. The reliance on 2D kinematic analysis of these strongman exercises is a potential major limitation of this research, whereby three-dimensional (3D) motion capture is considered the gold standard of describing athlete and object kinematics. Escamilla, et al. [34] compared 2D versus 3D kinematic analysis for athletes performing the conventional and sumo deadlift. Greater differences between joint/segment angles obtained using 2D versus 3D kinematic analyses were seen for the sumo deadlift than the conventional deadlift. The study suggested that these differences could be attributed to the multi-planar movement of the lower body in the sumo deadlift, which requires a wider stance and greater angle at which the feet are turned out compared to the conventional deadlift. Such results indicated that 2D kinematic analysis shows strong correlation with 3D kinematic analysis for knee, thigh and hip angular motion which is primarily performed in the sagittal plane only (such as the conventional deadlift). However, measurement errors are to be expected when performing 2D kinematic analysis on multi-planar movements in which some of the movement occurs at an angle that is not perpendicular to the field of view of the camera, as is often seen in many strongman exercises such as truck pull, tyre flip and weighted carries such as the farmers and yoke walk. Schurr, et al. [84] has also shown that 2D kinematic analysis is comparable to 3D motion capture when evaluating ankle, hip, knee and trunk angles in the sagittal plane during a single leg squat. There was however, no significant correlation between the two methods at any of the joints in the frontal plane except for a poor correlation at the knee. The discrepancies in the frontal plane were suggested to be attributed to the possible rotation of the ankle, hip and knee joints throughout the movement, as well as the high relative error of these joint motions that reflects the limited range of motion of these joints in the frontal compared to the sagittal plane.

Although McGill, et al. [36] successfully collected 3D motion data of athletes performing a number of strongman exercises, the focus was on the lower back and required data collection equipment to be attached to the posterior of the body only. While the use of a similar gold standard approach such as 3D optical motion capture may provide a greater quality of biomechanical measurements, especially for multi-planar movements that are not perpendicular to the camera's field of view as occurs relatively often in a number of strongman exercises, several difficulties in the use of this method may be experienced when applied to strongman exercises. Three-dimensional optical motion capture typically requires the placement of around 50 markers on various anatomical locations and planes of body segments to capture accurate translational and rotational motion [16]. Strongman exercises often require large, heavy, and awkward to position/lift implements (such as logs and stones) to be lifted over large portions of the body's anterior surface, thus it would appear difficult to successfully secure reflective markers to the required anatomical locations of an athlete's body whilst ensuring the markers would not be obscured or displaced when performing these exercises.

Recent developments in inertial measurement unit (IMU) based motion capture systems may provide a more feasible means of collecting 3D data than traditional 3D optical motion capture techniques [43]. Inertial measurement unit motion capture systems utilise a network of sensors located at various locations on the body, with the sensors secured either on the skin surface or on top of or beneath clothing. The development of such systems has seen various methods used for calibration, thus the versatility of locating the sensors on the body provides the potential to overcome issues seen when using traditional 3D motion capture systems [85]. Future studies may consider the use of IMU systems to improve the quality and breadth of motion data collected, with such an approach likely to be able to be utilised in both competition and training settings.

Force-velocity-power profiles of the barbell or the combined body-barbell system are becoming more commonly used to prescribe training load, and assess and/or predict the performance of an athlete [78, 86-89]. Two of the articles included in the current review obtained measurements of mean implement velocities, and mean force and power production during the strongman log lift [31, 69]. Presenting these measurements as a function of time or load may be of particular interest to strongman coaches and athletes, and strength and conditioning coaches where force-velocity-power training principles are considered. Future research may investigate the use of force-velocity-power profiling as a tool for prescribing training strategies and predicting the success of a strongman lift.

Standard EMG protocol procedures were generally followed in the two strongman studies that assessed muscle activity, however the inherent challenges associated with using EMG data to represent muscle activity must be acknowledged. These issues have generally been attributed to the noise generated at the skin-electrode interface due to the relative movement between the electrode, skin and muscle, the noise generated by electromagnetic radiation from nearby electrical appliances, and internal cross talk detected from surrounding muscles [90, 91]. Quantifying relative muscle activation also has a number of challenges, with normalisation to the EMG signal produced during MVC readings still most commonly utilised. There are however issues with normalising to MVC, especially when it is observed that one of the articles reviewed had muscle activity readings for several muscles greater than 100% of the athlete's pre-test MVC [36]. Ball and Scurr [92] compared repeated (across multiple days and weeks) EMG activity measurements of the triceps surae muscles whilst performing a variety of exercises including the squat jump, 20 m sprint, isometric heel raise and isokinetic plantar flexion. It was theorised that these exercises may provide a means of EMG normalisation reference values for the triceps surae muscles. While EMG activity measurements of all triceps surae muscles were reliable when performing the squat jump over multiple days and weeks, measurements taken when performing the 20 m sprint, isometric heel raise and isokinetic plantar flexion displayed less reliability, with reliability dependant on the duration between retests and the muscle being measured. Although the challenges associated with EMG readings are often acknowledged by researchers and a number of techniques have been developed to reduce the likelihood of misinterpretation of data [90], there are currently few practical alternative methods of acquiring and normalising muscle activity data.

For a body to displace a load, a muscular torque exceeding the load torque must be produced. The muscular torque can be defined as the product of force produced by the muscles spanning the joint and their respective muscular moment arm lengths, and the load torque can be defined as the product of the load force and the load moment arm length. Thus, the limb length and girth of the segment contribute substantially to the resistance moment arm length, muscular force produced and performance outcome of the exercise. Of the articles reviewed, only one study measured participant body composition and anthropometry, with the measurements obtained at one point of time from non-strongman (rugby) athletes who performed a range of strongman exercises [6]. Although the study found large to very large correlations between overall strongman competition performance and many anthropometric measures, measurements of limb lengths were not included in the analysis, thus presenting a potential gap in the research methodology.

A number of anthropometric measures have been shown to be related to the technique utilised [93] and performance outcomes [94, 95] of various strength based exercises including the bench press, clean and jerk, snatch and squat. Although Winwood, et al. [6] investigated the correlations between a number of simple anthropometric measures to the performance of athletes undertaking strongman exercises in a simulated competition, no study to date has assessed how anthropometric measures influence the kinematics, kinetics or muscle activity patterns of any strongman exercise. Such studies have however been conducted for the snatch weightlifting event, whereby a number of anthropometric measures were found to correlate to bar trajectory in elite female weightlifters [93]. Lower limb length showed strong correlation to horizontal bar displacement during the first pull phase of the snatch ($r = -0.93$) in female 75 kg body mass class athletes, while thigh and lower limb length showed strong correlation to horizontal bar displacement during the second pull phase (thigh: $r = -0.99$; lower limb: $r = -0.94$) in female 53 kg body mass class athletes [93]. Various body segment ratios also showed strong correlation to horizontal bar displacement across the body mass classes [93]. The exploration of the effect of anthropometrics (including limb lengths) on strongman biomechanics and the resultant performance measure of an athlete may be particularly interesting in strongman exercises due to the apparent variation in techniques used by strongman athletes of varying anthropometric characteristics. These data may be used by strongman coaches when teaching and improving the technique of an athlete so to enhance performance and prevent injury, while also being of interest to strength and conditioning coaches who may wish to prescribe such exercises to their non-strongman athletes.

## 2.7 CONCLUSION

The articles reviewed included the biomechanical analysis of eight different strongman exercises, with the farmers walk being the most commonly studied exercise as it appeared in five of the ten studies. The majority of the articles reviewed were more applicable to strength and conditioning coaches looking to implement strongman exercises into the training programmes of non-strongman athletes than to strongman athletes and coaches looking to improve strongman competition performance. Although the population size and training experience of participants varied between the studies reviewed, all studies consisted of male participants of a largely similar lower-level competitive standard, age and body mass. All studies reviewed were of a cross sectional observational study design and consisted of a warm-up and testing component. The biomechanical measurements collected throughout the testing components could be categorised into six primary areas, however due to the general awkward nature of strongman exercises the methods used to collect biomechanical measurements were often constrained to 2D motion capture and/or force plate analysis.

It is recommended future research in the field of strongman biomechanics should: assess under/un-researched strongman exercises; include a greater number of experienced strongman athletes (including female and lighter weight males); compare biomechanical measures between strongman athletes of different performance standards; consider the collection of biomechanical data over a range of loading conditions (e.g. competition loads); utilise advanced measurement technologies (e.g. 3D and/or IMU motion capture) for the collection of data; and consider how anthropometric measures (such as limb length) affect the biomechanics and performance of an athlete. With improvements in the research methodology of future strongman biomechanics studies, strength and conditioning coaches, and strongman athletes and coaches will be able to better understand: how strongman exercises may be used in wider strength and conditioning or injury rehabilitation practice; and the technique required to perform these exercises in a way that ensures the greatest performance outcome while minimising the risk of injury.

# CHAPTER 3:

# SYSTEMATIC REVIEW 2

# 3. The biomechanics and applications of strongman exercises: a systematic review

## 3.1 Preface

The purpose of this chapter was to further expand upon the results of Systematic Review 1 to gain a greater understanding of what is already known about the biomechanics of athletes performing strongman exercises. The general movement patterns, similarity to traditional weight training exercises and common everyday activities and biomechanical determinants of performance were discussed. This chapter, in conjunction with Chapter 2, assisted in shaping the strongman biomechanics experimental studies presented in Chapter 7 and Chapter 8. Question 1 *"What is already known about the biomechanics of athletes performing strongman exercises and where are the current gaps in the field of knowledge?"* was addressed in this chapter

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Hindle, B. R.; Lorimer, A.; Winwood, P.; Keogh, J. W. The biomechanics and applications of strongman exercises: A systematic review. Sports Medicine - Open 2019, 5, 49, doi:10.1186/s40798-020-0239-3.

## 3.2 ABSTRACT

**Background:** The sport of strongman is becoming increasingly popular, catering for females, lightweight and Masters competitors, with strongman exercises also being used by strength and conditioning coaches for a range of athletic groups. This, the second-part of a two-part systematic review, was conducted to examine our current understanding of the biomechanics of strongman exercises, with a view to: improve strongman athlete performance; provide biomechanical evidence supporting the transferability of strongman exercises to the strength and conditioning/rehabilitation programs of athletes, tactical personnel and other manual labour occupations; and identify gaps in the current knowledge of the biomechanics of strongman exercises. **Methods:** A two-level search term strategy was constructed and used to search five databases for studies relevant to strongman exercises and biomechanics. **Results:** Eleven articles adherent to the inclusion criteria were returned from the search. The studies provided preliminary biomechanical analysis of various strongman exercises including the key biomechanical performance determinants of the farmers walk, heavy sled pull and tyre flip. When compared with lower performing (LP) athletes, higher performing (HP) athletes undertaking the farmers walk and heavy sled pull were characterised by a greater stride length (HP: 1.83 ± 0.04 m; LP: 1.40 ± 0.17 m) and stride rate (HP: 2.01 ± 0.13 Hz; LP: 1.83 ± 0.04 Hz), and reduced ground contact time (HP: 0.29 ± 0.02 s; LP: 0.34 ± 0.03 s), while HP athletes performing the tyre flip were characterised by a reduced second pull phase time when compared with LP athletes (HP: 0.38 ± 0.17 s; LP: 1.49 ± 0.92 s). Qualitative comparison of carrying/walking, pulling and static lifting strongman, traditional weight training exercises (TWTE) and common everyday activities (CEA) like loaded carriage and resisted sprinting were discussed to further our understanding of the determinants of various strongman exercises and their applications to strength and conditioning practice. A lack of basic quantitative biomechanical data of the yoke walk, unilateral load carriage, vehicle pull, atlas stone lift and tyre flip, and biomechanical performance determinants of the log lift were identified. **Conclusions:** Future research in the identified areas of strongman biomechanics is expected to provide strongman coaches with valuable insight into the biomechanical determinants of performance in a wider range of strongman exercises. Furthermore, a greater understanding of the potential training adaptations and risks expected when performing and/or incorporating strongman exercises into strength and conditioning or injury rehabilitation programs will be gained through further research.

Key words*:* Weightlifting, kinematics, kinetics, motion analysis.

## 3.3 BACKGROUND

Humankind's obsession with strength dates back to antiquity, where wrestling matches were used to prove strength by the Greeks and Egyptians. To gain the strength, endurance and power that were required to defeat their opponent, men would train by lifting stones of varying size, mass and shape [1]. Around the twelfth century in Scotland, the Highland Games became popular for determining the strongest competitor, with competitors required to perform running, jumping, lifting and wrestling tasks to prove their strength. Contemporary Highland Games have evolved to include heavy throwing and lifting events. Increasing popularity and international awareness of the Highland Games throughout the twentieth century led to 'The World's Strongest Man', first held in 1977 [2, 3]. In recent years the sport of strongman has seen rapid growth with competitions at local, regional, national and international levels, and a range of divisions created to cater for age, body mass, sex and experience [14].

Modern strongman competitions require an athlete to carry, pull or lift heavy and awkward objects [4]. The exercises developed for strongman competitions are generally heavier versions of common everyday activities (CEA) or more awkward/challenging variations of traditional weight training exercises (TWTE) such as the squat, deadlift and clean and press [51]. In contrast to TWTE, which typically require the weight to be lifted vertically and use bilateral load distribution, strongman exercises often require the athlete to move loads horizontally, test the athlete in multiple planes and incorporate phases of unilateral and bilateral loading [5, 6]. Strongman exercises typically involve equipment such as: loaded frames, kegs and bags for carrying; loaded sleds and vehicles for pulling; and stones, logs, tyres and oversized dumbbells for lifting (Figure 3.1) [13].

As the sport of strongman continues to increase in popularity and the use of such exercises in strength and conditioning programs becomes more common for non-strongman athletes, research in this area continues to grow. In field of current strongman research, researchers have investigated the use of strongman implements by strength and conditioning coaches of non-strongman athletes [7], the acute and chronic physiological adaptations to strongman type training [4, 50, 51, 57-59], the training and tapering practices of strongman athletes [3, 52-56], and the injury epidemiology of strongman athletes [14]. The literature now also includes narrative reviews and opinion pieces suggesting how strongman exercises may be best used in the strength and conditioning programs of non-strongman athletes [3, 52, 56, 59].

As the authors explored the current field of strongman biomechanics research, it became apparent that in order to thoroughly report and discuss all data on the given topic, a two-part systematic review was required. The first part of the systematic review was conducted to assess the research methods used in existing strongman biomechanics research, whereby a summary of the exercises, study designs, study populations and biomechanical methods/measurements used were reported [12].

The primary objective of conducting this, the second part to the original systematic review, was to determine our current understanding of the biomechanics of strongman exercises specifically, with a view to: 1) improve athlete performance by providing athletes and coaches with a greater understanding of the key biomechanical determinants of performance of these exercises; 2) provide biomechanical evidence supporting the transferability of strongman exercises to the strength and conditioning/rehabilitation programs of athletes, tactical operators (e.g. military, army) and other manual labour occupations; and 3) identify the gaps in the current knowledge of the biomechanics of strongman exercises. Such information would be valuable to the strongman coach and athlete, the strength and conditioning coach who may use these exercises with their non-strongman athletes as well as the researcher who may design future studies to address some of the key limitations of the literature.


Figure 3.1 Examples of strongman exercises: a) atlas stone lift; b) farmers walk; c) heavy sled pull; d) keg walk; e) log lift; f) suitcase carry; g) tyre flip; h) yoke walk. Images reprinted with permission from owner Hiroya Togawa.

## 3.4 METHODS

### 3.4.1 EXPERIMENTAL APPROACH TO THE PROBLEM

The review process followed the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) guidelines on reporting items for a systematic review and the associated PRISMA checklist [60]. Due to the nature of the systematic review Institutional Review Board approval to conduct this investigation and registration with the International Prospective Register of Systematic Reviews (PROSPERO) was not deemed to be relevant. A set of inclusion/exclusion criteria were developed prior to undertaking the search process. The criteria specified only peer reviewed journal articles assessing anthropometric, kinematic, kinetic, muscular activity or spatiotemporal measures of athletes performing common strongman exercises would be included in the review. Articles including injured athletes, sled loads less than the body mass of the athlete, and studies where researchers focused on the use of the sled pull for the purpose of sprint performance would be excluded from the primary literature reviewed. No limitations were placed on language or year of publication. The data from the included articles were then extracted, analysed and discussed based on the strongman exercise type.

### 3.4.2 LITERATURE SEARCH AND SCREENING

To identify all articles in which biomechanical analysis of a strongman exercise had been undertaken, a two-level keyword search consisting of terms associated with strongman exercises, lifts and training methods (level one), and terms associated with general biomechanical parameters (level two) was constructed using Boolean operators. An initial search up to and including 25 October 2018 was conducted using AusportMed, CINAHL, Embase, Medline (Ovid) and SPORTDiscus for part one of the systematic review [12]. The search was repeated for this systematic review (part two) on 25 March 2019 so to identify any articles published since the initial search. The full search strategy used for each database can be seen in the Appendix 3.

The results from the five databases were imported into an online systematic review management software Rayyan (Doha, Qatar) before being distributed to two independent reviewers [96]. The two reviewers cast either "include", "exclude" or "maybe" votes for each article throughout the title/abstract screening process and "include" or "exclude" votes during the full text screening process in accordance with the predefined inclusion/exclusion criteria. During the full text screening process, reviewers were required to provide reason based on a list of hierarchical criteria as to why they were excluding a study from further review. Where disagreement in voting or reasoning for exclusion occurred, a consensus meeting was held to form agreement between parties. After identifying all eligible articles, the reference list of each article was examined, and Google Scholar was used to perform a forward citation search to identify any potentially eligible articles not returned during the database search.

### 3.4.3 Risk of bias and quality assessment

No single risk of bias/quality assessment tool appeared entirely suitable to perform a meaningful assessment of the identified literature, which were all of a cross-sectional observational study design. An appropriate checklist was developed by the authors using tools established by other systematic reviews containing studies of a similar design [61-68], with this adapted checklist used by Hindle, et al. [12] in a systematic review of the biomechanical research methods used to evaluate strongman exercises. Reviewers awarded a star (⋆) in support of the criteria or no star where the criteria was not met, with any disagreement in voting between reviewers settled by a consensus meeting. The risk of bias score was calculated for each article based on a total maximum achievable score of 16 stars, and categorised in accordance with Davids, et al. [62] where articles scoring $\geq$ 11 stars were categorised as having a low risk of bias, articles scoring 6 – 10 stars categorised as having a satisfactory risk of bias, and articles scoring $\leq$ 5 stars categorised as having a high risk of bias.

### 3.4.4 Limitations

The systematic review was conducted in two parts so to ensure its exhaustive nature and capture as much information on the biomechanical analysis of strongman exercises. One limitation of this method is the lapse in time between the publication of the initial systematic review [12] and this, the second part of the review. This limitation resulted in the search of databases being conducted a second time and thus enabled the potential for additional studies being included in the second part of the review. The second limitation of this systematic review is in the tool used for the risk of bias/quality assessment, whereby it may be seen that using a risk of bias/quality assessment tool developed by the author team may add an additional level of bias to the systematic review itself. The use of Google Scholar for forward citation tracking may be considered a minor limitation to the systematic review due to the unreliability sometimes associated with the platform.

## 3.5 RESULTS

### 3.5.1 LITERATURE SEARCH AND SCREENING

The search of the five databases on 25 March 2019 returned 877 results, of which eleven articles were identified as being adherent to the inclusion criteria (Figure 3.2). The outcome of the screening process and resultant PRISMA flowchart differed slightly to Hindle, et al. [12] as the independent reviewers agreed upon excluding a greater number of articles at the title/abstract level due to familiarisation with these articles during previous full text screening.

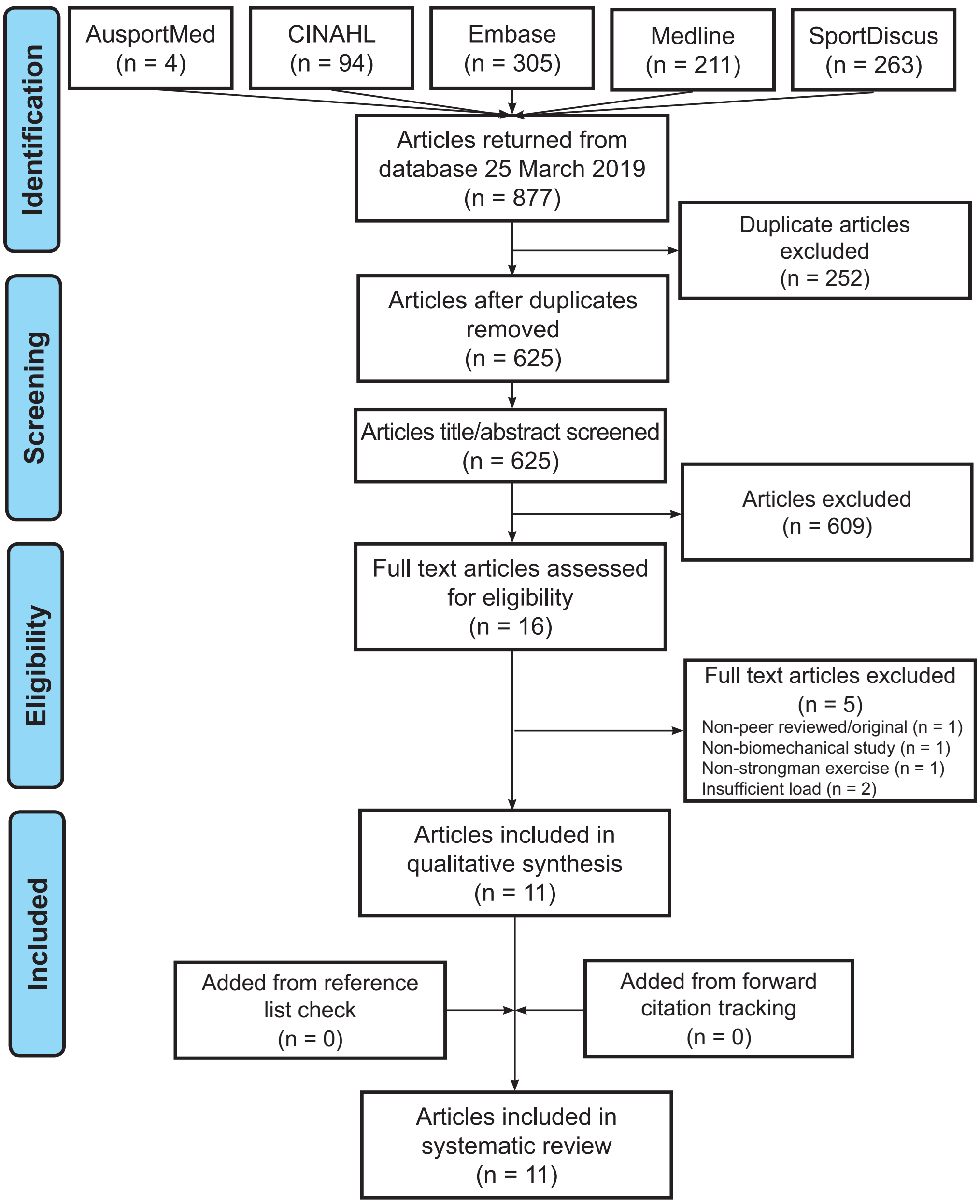


Figure 3.2 Flowchart of screening process.

### 3.5.2 Risk of bias and quality assessment

Within each study, the objectives/purpose of undertaking the study and the characteristics of the study population were clearly detailed. Statistical methods used within each study were appropriate. Testable hypotheses were proposed within the majority of studies and well validated equipment were mostly used to collect measures. All articles were classified as having a satisfactory or low risk of bias (Table 3.1).

Table 3.1 Risk of bias and quality assessment.

| Article | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Score (/16) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Holmstrup, et al. [97] | - | ✶ | ✶ | ✶ | ✶ | - | - | ✶ | - | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | 12 (L) |
| Keogh, et al. [29] | ✶ | ✶ | ✶ | - | ✶ | - | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | ✶ | ✶ | 13 (L) |
| Keogh, et al. [70] | ✶ | ✶ | ✶ | - | ✶ | - | - | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | ✶ | ✶ | 11 (L) |
| Keogh, et al. [30] | ✶ | ✶ | ✶ | - | ✶ | - | - | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | 13 (L) |
| McGill, et al. [36] | - | ✶ | ✶ | - | ✶ | ✶ | - | - | - | - | ✶ | ✶ | ✶ | - | - | - | 7 (S) |
| Stastny, et al. [71] | ✶ | ✶ | - | - | ✶ | - | - | ✶ | - | ✶ | ✶ | - | - | - | ✶ | ✶ | 8 (S) |
| Renals, et al. [69] | ✶ | ✶ | ✶ | - | ✶ | ✶ | - | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | - | ✶ | 12 (L) |
| Winwood, et al. [6] | ✶ | ✶ | ✶ | - | ✶ | - | - | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | - | ✶ | 11 (L) |
| Winwood, et al. [5] | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | - | 13 (L) |
| Winwood, et al. [32] | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | - | 13 (L) |
| Winwood, et al. [31] | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | ✶ | ✶ | ✶ | ✶ | ✶ | ✶ | - | - | - | 12 (L) |

Method for assessing risk of bias: (1) study design was stated clearly; (2) the study objective/purpose is clearly stated; (3) the study has a clearly testable hypothesis; (4) the study clearly states the inclusion criteria for participants; (5) the characteristics of the population are well detailed; (6) the study population is representative of the intended population for which the research is aimed; (7) a justification for the selection of the sample/study population size was provided; (8) the methods used throughout testing are well detailed; (9) the measurement tools used throughout the study are reliable and have been validated; (10) detail on the statistical methods used was provided; (11) the statistical methods used to analyse the data were appropriate; (12) the results of the study are well detailed; (13) the information provided in the paper is sufficient information was provided so to allow the reader to make an unbiased assessment of the study findings; (14) confounding factors within the study are identified; (15) study funding/conflicts of interest were acknowledged; (16) limitations to the study were identified. *L* low risk of bias (11–16 ✶), *S* satisfactory risk of bias (6–10 ✶), *H* high risk of bias (0–5 ✶).

### 3.5.3 Study results and data synthesis

Strongman exercises which have had a biomechanical assessment in at least one of the eleven studies were the atlas stone lift, farmers walk, heavy sled/vehicle pull, log lift, keg walk, suitcase carry, tyre flip and yoke walk (Figure 3.1). For a description of these exercises the reader is directed to Hindle, et al. [12]. The eight strongman exercises can be categorised into three exercise types: carrying/walking, pulling, and static lifting (Figure 3.3). The comparative analysis within each of the studies could be categorised into three main areas: comparisons based on the performance outcome of the exercise [6, 29, 30, 70, 97]; within exercise comparisons (between phase) [5, 29, 30, 32, 71]; and between exercise comparisons [5, 31, 32, 36, 69]. The results from the eleven studies will be presented in the format outlined in Figure 3.3.

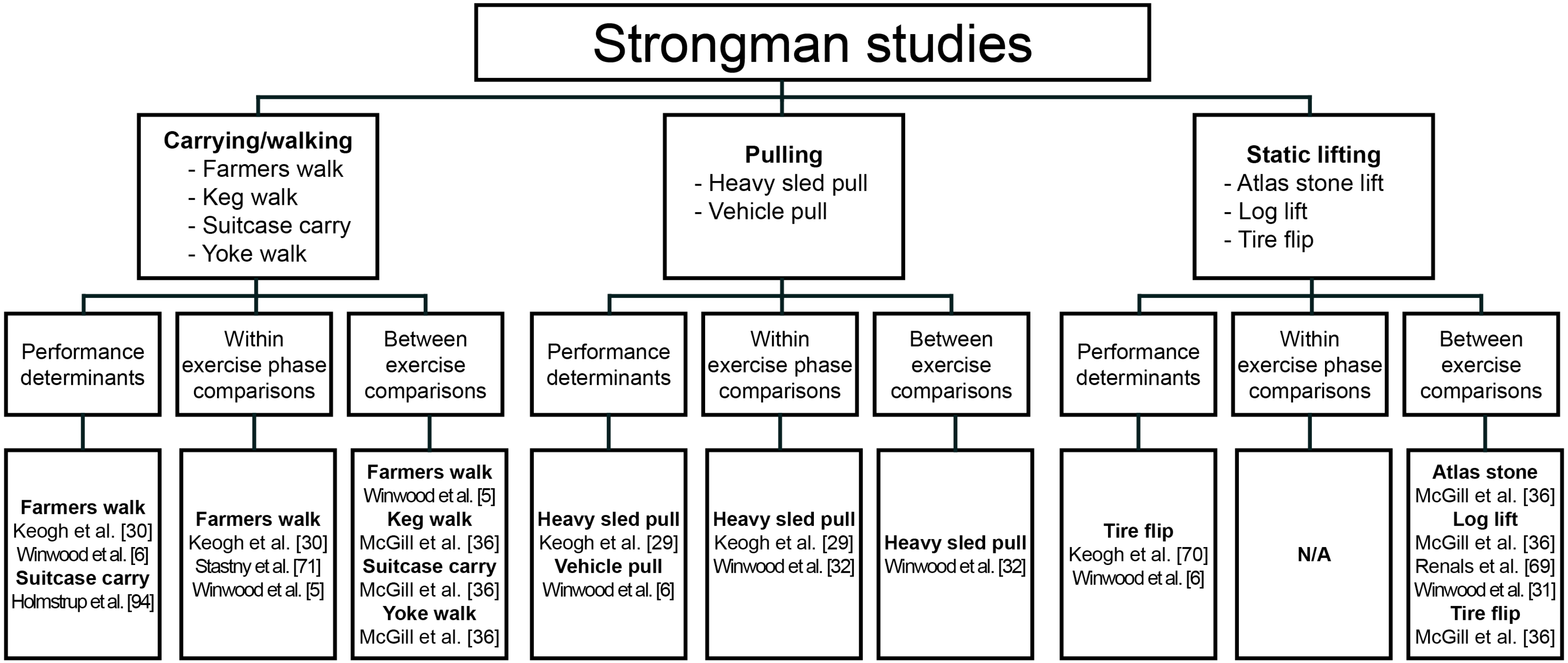

Figure 3.3 Study results structure.

### 3.5.4 CARRYING/WALKING EXERCISES

The carrying/walking strongman exercises biomechanically analysed were the farmers walk, keg walk, suitcase carry and yoke walk. The farmers walk was the most studied enabling within and between study comparison. (Table 3.2).

#### 3.5.4.1 *BIOMECHANICAL DETERMINANTS OF PERFORMANCE*

Comparing spatiotemporal measures of higher performing (HP) and lower performing (LP) athletes, greater performance in the farmers walk was associated with a reduced ground contact time, increased stride length and increased stride rate during the maximum velocity phase of the walk [30]. Maximum velocity was reached at different stages of the farmers walk depending on the athlete's performance level, with HP athletes reaching a maximum velocity in the final 17 – 20 m section of the walk, while LP athletes reached a maximum velocity in the middle 8.5 – 11.5 m section of the walk [30].

Higher performing athletes had significantly greater dorsiflexion of the ankle at foot strike and toe off, a more horizontally aligned thigh at foot strike, and greater ankle and thigh range of motion (ROM) [30]. Measures of flexed arm girth, muscle mass and total system force (calculated as the sum of the athlete's body mass and one repetition maximum (1RM) squat) were reported to be the greatest anthropometric determinants of performance in the farmers walk exercise (flexed arm girth: $r = 0.46$; muscle mass: $r = 0.49$; total system force: $r = 0.64$) [6]. Participants with a greater percentage of fat free mass were also found to be able to carry greater loads during the suitcase carry before their technique and posture were compromised [97].

#### 3.5.4.2 *WITHIN EXERCISE BIOMECHANICAL DIFFERENCES*

Reduced ground contact time and increased stride length was observed in the maximum velocity phase of the farmers walk when compared to the acceleration and sub-maximal velocity phase [5, 30]. Comparing acceleration, sub-maximal and maximal velocity phases; greater ankle dorsiflexion and knee flexion at foot strike, greater knee flexion and a more horizontally oriented thigh at toe off, increased ankle ROM, and reduced thigh and knee ROM was observed during the acceleration phase [30]. Stastny, et al. [71] compared muscle activation patterns between athletes of varying muscle activation strength ratios, finding athletes with a hip abductor (HAB) to hamstring maximum voluntary contraction (MVC) ratio $< 1$ and/or a HAB to quad MVC ratio $< 0.5$, tended to have greater activation of the gluteus medius muscle during the farmers walk.

#### 3.5.4.3 *BETWEEN EXERCISE BIOMECHANICAL DIFFERENCES*

Significantly greater stride rate, and reduced stride length and ground contact time have been reported in the farmers walk when compared to unloaded walking [5]. The farmers walk was also observed to result in greater anterior tilt of the trunk, dorsiflexion of the ankle and extension of the knee at foot strike, and increased mean and peak anterior, posterior, vertical and medial ground reaction forces [5].

Comparison of joint/segment angular kinematics of the initial lift of the farmers walk (farmers lift) to the deadlift indicated the farmers lift to be primarily characterised by a more vertical trunk position throughout the majority of the lift except for at lift completion, leading to an overall reduced trunk ROM [5]. Greater mean vertical, anterior, and resultant anterior/posterior forces were also reported in the farmers lift [5]. The only reported significant differences in lumbar joint angular kinematics during the carrying/walking exercises was a greater peak twist angle during the right hand suitcase carry (~11°) than the farmers walk (~8°) and yoke walk (~7°), which were all significantly greater than the left hand suitcase carry (~6°) [36].

The farmers walk and yoke walk bilateral load carriage exercises were reported to result in significantly greater muscular compression, anterior/posterior spine muscular loading, muscular axial twist stiffness and flexion/extension stiffness than the right/left hand suitcase carry unilateral load carriage exercise [36]. McGill, et al. [36] reported greater activation of a number of key spinal musculature when performing the yolk and farmers walk than when performing the left/right hand suitcase carry. Further significant differences in muscle activation patterns are presented in Table 3.3.

Table 3.2 Walking/carrying results comparisons - farmers walk.

| | Winwood, et al. [5] | | | Keogh, et al. [30] | | | |
|---|---|---|---|---|---|---|---|
| | Farmers walk | Unloaded walk | ES | Higher performer | Lower performer | ES | Group ave. |
| Spatiotemporal | | | | | | | |
| Ground contact time (s) | 0.46 ± 0.06* (MVP) | 0.67 ± 0.06 (MVP) | -3.50 | 0.29 ± 0.02† (MVP)× | 0.34 ± 0.03 (SVP)× | -1.96 | 0.30 ± 0.03☼ (MVP) |
| | 0.53 ± 0.09* (AP) | 0.77 ± 0.07 (AP) | -3.00 | 0.39 ± 0.04† (AP) | 0.32 ± 0.03 (AP) | 1.98 | 0.36 ± 0.04 (AP) |
| Stride rate (Hz) | 1.42 ± 0.17* (MVP) | 0.88 ± 0.06 (MVP) | 4.20 | 2.01 ± 0.13† (MVP)× | 1.83 ± 0.04 (SVP)× | 1.88 | 1.97 ± 0.13☼ (MVP) |
| | 1.21 ± 0.12* (AP) | 0.82 ± 0.04 (AP) | 4.40 | 1.88 ± 0.10† (AP) | 1.64 ± 0.12 (AP) | 2.17 | 1.79 ± 0.14 (AP) |
| Stride length (m) | 1.04 ± 0.12* (MVP) | 1.43 ± 0.11 (MVP) | -3.40 | 1.83 ± 0.04† (MVP)× | 1.40 ± 0.17 (SVP)× | 3.48 | 1.67 ± 0.10☼ (MVP) |
| | 0.85 ± 0.19* (AP) | 1.33 ± 0.11 (AP) | -3.10 | 1.38 ± 0.16 (AP) | 1.33 ± 0.09 (AP) | 0.39 | 1.32 ± 0.12 (AP) |
| Average velocity (m/s) | 1.48 ± 0.19 (MVP) | 1.26 ± 0.15 (MVP) | 1.28 | 3.66 ± 0.17† (MVP) | 2.83 ± 0.36 (MVP) | 2.95 | 3.29 ± 0.38☼ (MVP) |
| | 1.05 ± 0.21 (AP) | 1.11 ± 0.09 (AP) | -0.37 | 2.61 ± 0.38 (AP) | 2.19 ± 0.27 (AP) | 1.27 | 2.41 ± 0.32 (AP) |
| Kinematic | | | | | | | |
| Ankle angle at FS (°) | 95.0 ± 3.00* (MVP) | 105 ± 2.00 (MVP) | -3.80 | 101 ± 6.00† (SVP)× | 113 ± 5.00 (MVP)× | -2.17 | 110 ± 9.00 (MVP) |
| | 96.00 ± 6.00* (AP) | 105 ± 2.00 (AP) | -2.30 | 99.0 ± 8.00 (AP) | 106 ± 6.00 (AP) | -0.99 | 100 ± 8.00 (AP) |
| Ankle angle at TO (°) | 100 ± 5.00* (MVP) | 115 ± 9.00 (MVP) | -2.10 | 118 ± 5.00 (MVP)× | 117 ± 7.00 (SVP)× | 0.16 | 114 ± 6.00 (MVP) |
| | 105 ± 6.00 (AP) | 118 ± 5.00 (AP) | -2.30 | 108 ± 4.00† (AP) | 114 ± 3.00 (AP) | -1.70 | 111 ± 5.00 (AP) |
| Ankle ROM (°) | 4.00 ± 4.00 (MVP) | 10.0 ± 10.0 (MVP) | -0.70 | -10.0 ± 4.00† (SVP) | 1.00 ± 5.00 (MVP)× | -2.43 | -4.00 ± 7.00☼ (MVP) |
| Knee angle at FS (°) | 154 ± 7.00* (MVP) | 178 ± 6.00 (MVP) | -3.70 | 156 ± 6.00 (MVP)× | 166 ± 16.0 (SVP)× | -0.83 | 155 ± 6.00☼ (MVP) |
| | 150 ± 9.00* (AP) | 174 ± 10.0 (AP) | -2.50 | 147 ± 7.00 (AP) | 151 ± 5.00 (AP) | -0.66 | 150 ± 6.00 (AP) |
| Thigh angle at FS (°) | 34.0 ± 6.00* (MVP) | 23.0 ± 7.00 (MVP) | 1.80 | 38.0 ± 3.00† (MVP)× | 31.0 ± 4.00 (SVP)× | 1.98 | 34.0 ± 3.00 (MVP) |
| Thigh ROM (°) | -19.0 ± 5.00 (MVP) | -22.0 ± 10.0 (MVP) | 0.40 | -44.0 ± 4.00† (MVP)× | -35.0 ± 6.00 (SVP)× | -1.77 | -38.0 ± 4.00☼ (MVP) |
| Trunk angle at FS (°) | 78.0 ± 3.00* (MVP) | 90.0 ± 2.00 (MVP) | -4.10 | – | – | | – |
| | 69.0 ± 5.00* (AP) | 85.0 ± 2.00 (AP) | -4.30 | – | – | | – |
| Trunk angle at TO (°) | 76.0 ± 4.00* (MVP) | 87.0 ± 2.00 (MVP) | -3.20 | – | – | | – |
| | 70.0 ± 5.00* (AP) | 84.0 ± 4.00 (AP) | -3.40 | – | – | | – |

Table 3.2 continued.

| | Winwood, et al. [5] | | | Keogh, et al. [30] | | | |
|---|---|---|---|---|---|---|---|
| | Farmers walk | Unloaded walk | ES | Higher performer | Lower performer | ES | Group ave. |
| Kinetic | | | | | | | |
| Mean anterior GRF (N) | 127 ± 31.0* (MVP) | 83.0 ± 25.0 (MVP) | 1.60 | – | – | | – |
| Peak anterior GRF (N) | 447 ± 98.0* (MVP) | 259 ± 53.0 (MVP) | 2.40 | – | – | | – |
| Mean medial GRF (N) | 120 ± 41.0* (MVP) | 70.0 ± 36.0 (MVP) | 1.30 | – | – | | – |
| Peak medial GRF (N) | 241 ± 73.0* (MVP) | 120 ± 62.0 (MVP) | 1.80 | – | – | | – |
| Mean posterior GRF (N) | 159 ± 45.0* (MVP) | 94.0 ± 34.0 (MVP) | 1.60 | – | – | | – |
| Peak posterior GRF (N) | 389 ± 143* (MVP) | 211 ± 77.0 (MVP) | 1.50 | – | – | | – |
| Mean vertical GRF (N) | 2540 ± 376* (MVP) | 1030 ± 247 (MVP) | 4.70 | – | – | | – |
| Peak vertical GRF (N) | 3630 ± 608* (MVP) | 1510 ± 387 (MVP) | 4.10 | – | – | | – |
| Peak lateral GRF (N) | 210 ± 73.0* (MVP) | 119 ± 45.0 (MVP) | 1.50 | – | – | | – |

All data is reported as means ± standard deviation, unless specified otherwise. Effect sizes reported for between exercise [5] and between performance standard [30], A positive effect size indicates the left-hand column (farmers walk or higher performer) had a greater value than the respective right-hand column (unloaded walk or lower performer).* significant difference to unloaded walking, † significant difference to low performing athletes, ☼ significant difference to acceleration phase, ˣ comparison between phase based on distance, *AP* acceleration phase, *ave* average, *ES* effect size, *GRF* ground reaction force, *MVP* maximum velocity phase, *SVP* submaximal velocity phase.

Table 3.3 Significant differences in muscle activation and kinetic outcomes between the walking/carrying exercises.

| | Farmers walk [36] | LH suitcase carry [36] | RH suitcase carry [36] | Yoke walk [36] |
|---|---|---|---|---|
| Muscle activity (%MVC) | | | | |
| Left upper erector spinae | 77.6 ± 29.3 ‡ | 47.1 ± 6.20 | 32.4 ± 4.60 *☼ | 69.3 ± 17.5 ‡ |
| Right upper erector spinae | 91.4 ± 54.7 † | 24.9 ± 17.6 *‡☼ | 52.1 ± 17.3 † | 65.6 ± 14.4† |
| Left lower erector spinae | 106 ± 51.1 † | 31.6 ± 10.1 *‡☼ | 77.4 ± 21.3 † | 79.2 ± 10.2 † |
| Right lower erector spinae | 144 ± 36.7 ‡ | 96.9 ± 20.4 ‡ | 44.1 ± 9.10 *†☼ | 107 ± 31.5 ‡ |
| Left latissimus dorsi | 169 ± 55.4 *‡ | 97.4 ± 55.7 | 68.9 ± 23.2 ☼ | 51.9 ± 26.4 ☼ |
| Right latissimus dorsi | 152 ± 26.7 *† | 65.3 ± 6.20 ☼ | 91.4 ± 39.1 | 45.5 ± 31.7 ☼ |
| Left external oblique | 39.3 ± 30.6 † | 12.6 ± 5.30 *‡☼ | 61.5 ± 21.9 † | 47.5 ± 31.7 † |
| Right external oblique | 50.4 ± 17.4 ‡ | 65.1 ± 24.4 ‡ | 29.0 ± 17.8 *†☼ | 58.8 ± 17.4 ‡ |
| Right rectus abdominis | 13.3 ± 3.80 | 14.6 ± 4.50 | 5.60 ± 1.80 * | 22.3 ± 18.1 ‡ |
| Right gluteus maximus | 114 ± 70.3 ‡ | 78.2 ± 39.5 | 50.5 ± 31.2 *☼ | 113 ± 52.1 ‡ |
| Right gluteus medius | 108 ± 66.9 ‡ | 64.1 ± 38.7 | 57.3 ± 23.6 *☼ | 108 ± 69.7 ‡ |
| Right bicep femoris | 54.0 ± 13.7 † | 31.2 ± 7.50 *‡ ☼ | 48.3 ± 8.6 † | 61.7 ± 6.30 † |
| Right rectus femoris | 77.4 ± 35.6 | 41.1 ± 9.20 * | 56.5 ± 11.5 * | 107 ± 23.5 †‡ |
| Kinetic | | | | |
| Muscular anterior/posterior shear (N) | 2800 † | 1680 ☼ | 1160 | 1890 |
| Muscular compressive load (N) | 7900 † | 5800 *☼ | 6700 | 7800 † |
| Muscular axial twist stiffness (Nm/rad) | 27,200 †‡ | 19,100 ☼ | 24,600 ☼ | 25,900 |
| Muscular flexion/extension stiffness (Nm/rad) | 35,600 | 24,000 * | 27,500 | 38,600 † |

All data is reported as means ± standard deviation, unless specified otherwise. * significant difference to yoke walk, † significant difference to left hand suitcase carry, ‡ significant difference to right hand suitcase carry, ☼ significant difference to farmers walk, *LH* left hand, *MVC* maximum voluntary contraction *RH* right hand.

### 3.5.5 PULLING EXERCISES

The only pulling strongman exercise biomechanically analysed was the heavy sled pull, while anthropometric measures were assessed and correlated to performance in the truck/vehicle pull. Basic within and between study comparison of the heavy sled pull could be conducted using the available data (Table 3.4).

#### 3.5.5.1 *BIOMECHANICAL DETERMINANTS OF PERFORMANCE*

Greater performance during the heavy sled pull was characterised by an increased stride length, stride rate and reduced ground contact time [29]. Higher performing athletes also generally exhibited a more vertical trunk position and greater knee extension at foot strike [29]. Measures of flexed arm girth, mid-thigh girth, and total system force (calculated as the sum of the athlete's body mass and 1RM squat) were reported to be the strongest anthropometric determinants of performance in the vehicle pull (flexed arm girth: $r = 0.74$; mid-thigh girth: $r = 0.70$; total system force: $r = 0.68$) [6].

#### 3.5.5.2 *WITHIN EXERCISE BIOMECHANICAL DIFFERENCES*

The maximum velocity phase of the heavy sled pull was associated with greater stride length, knee extension at foot strike [29, 32], swing time, and a more horizontal trunk and vertical thigh position at foot strike and toe off [29] than the submaximal velocity and acceleration phase. Conversely, the initial stride saw greater mean resultant anterior/posterior and mean resultant medial/lateral ground reaction forces than strides at 2 – 3 m [32].

#### 3.5.5.3 *BETWEEN EXERCISE BIOMECHANICAL DIFFERENCES*

The back squat involved significantly greater hip and knee ROM than the heavy sled pull [32]. Greater knee flexion and a more vertical trunk position at the start of the concentric phase, and greater extension of the hip and knee at the point of maximum knee extension were also recorded during the squat [32]. The distinct differences in body positioning for back squat vs. sled pull were supported by greater peak and mean vertical force during the back squat, and significantly greater peak and mean anterior force during the heavy sled pull [32].

Table 3.4 Pulling significant results comparisons - heavy sled pull.

| | Winwood, et al. [32] | | | Keogh, et al. [29] | | | |
|---|---|---|---|---|---|---|---|
| | Heavy sled pull | ES | Back squat | Higher performer | Lower performer | ES | Group ave. |
| Spatiotemporal | | | | | | | |
| Ground contact time (s) | 0.35 ± 0.04 (MVP) | -0.85 | – | 0.33 ± 0.04† (MVP) | 0.76 ± 0.37 (MVP) | -1.63 | 0.48 ± 0.23 (MVP) |
| | 0.38 ± 0.03 (AP) | | – | 0.42 ± 0.19 (AP) | 0.57 ± 0.23 (AP) | -0.71 | 0.53 ± 0.32 (AP) |
| Stride rate (s) | 1.42 ± 0.14 (MVP) | 0.07 | – | 1.63 ± 0.12† (MVP) | 1.10 ± 0.42 (MVP) | 1.72 | 1.37 ± 0.39 (MVP) |
| | 1.41 ± 0.14 (AP) | | – | 1.50 ± 0.55 (AP) | 1.29 ± 0.37 (AP) | 0.45 | 1.45 ± 0.50 (AP) |
| Swing time (s) | 0.33 ± 0.04 (MVP) | 0.39 | – | 0.29 ± 0.03 (MVP) | 0.27 ± 0.05 (MVP) | 0.49 | 0.28 ± 0.04☼ (MVP) |
| | 0.31 ± 0.06 (AP) | | – | 0.28 ± 0.07† (AP) | 0.23 ± 0.05 (AP) | 0.82 | 0.25 ± 0.06 (AP) |
| Stride length (m) | 1.29 ± 0.17☼ (MVP) | 1.81 | – | 1.29 ± 0.26† (MVP) | 0.80 ± 0.16 (MVP) | 2.27 | 1.03 ± 0.26☼ (MVP) |
| | 1.00 ± 0.15 (AP) | | – | 0.85 ± 0.25† (AP) | 0.65 ± 0.04 (AP) | 1.12 | 0.74 ± 0.28 (AP) |
| Kinematic | | | | | | | |
| Average velocity (m/s) | 1.83 ± 0.22☼ (MVP) | 2.44 | – | 2.08 ± 0.08† (MVP) | 0.99 ± 0.50 (MVP) | 3.04 | 1.61 ± 0.55☼ (MVP) |
| | 1.39 ± 0.13 (AP) | | – | 1.22 ± 0.20† (AP) | 0.79 ± 0.32 (AP) | 1.61 | 1.04 ± 0.30 (AP) |
| Knee angle at FS (°) | 114 ± 6.00☼ (MVP) | 1.38 | – | 132 ± 9.00† (MVP) | 112 ± 22.0 (MVP) | 1.19 | 124 ± 18.0☼ (MVP) |
| | 103 ± 9.00 (AP) | | – | 125 ± 12.0† (AP) | 110 ± 10.0 (AP) | 1.36 | 116 ± 13.0 (AP) |
| Knee angle at TO (°) | 138 ± 14.0 (MVP) | 0.35 | – | 153 ± 7.00 (MVP) | 148 ±10.0 (MVP) | 0.59 | 149 ± 9.00☼ (MVP) |
| | 133 ± 14.0 (AP) | | – | 148 ± 14.0† (AP) | 138 ± 17.0 (AP) | 0.65 | 141 ± 15.0 (AP) |
| Thigh angle at FS (°) | – | – | – | 23.0 ± 5.00† (MVP) | 19.0 ± 5.0 (MVP) | 0.80 | 21.0 ± 5.00☼ (MVP) |
| | – | | – | 14.0 ± 10.0 (AP) | 16.0 ± 8.00 (AP) | -0.22 | 15.0 ± 10.0 (AP) |
| Trunk angle at FS (°) | 61.0 ± 13.0 (MVP) | -0.67 | – | 41.0 ± 7.00† (MVP) | 8.00 ± 29.0 (MVP) | 1.56 | 26.0 ± 24.0☼ (MVP) |
| | 77.0 ± 30.0 (AP) | | – | 29.0 ± 17.0† (AP) | 2.00 ± 16.0 (AP) | 1.64 | 14.0 ± 21.0 (AP) |
| Trunk angle at TO (°) | 61.0 ± 11.0 (MVP) | -0.49 | – | 41.0 ± 9.00† (MVP) | 14.0 ± 25.0 (MVP) | 1.59 | 28.0 ± 21.0☼ (MVP) |
| | 69.0 ± 20.0 (AP) | | – | 31.0 ± 15.0† (AP) | 10.0 ± 14.0 (AP) | 1.45 | 19.0 ± 19.0 (AP) |

Table 3.4 continued.

| | Winwood, et al. [32] | | | Keogh, et al. [29] | | | |
|---|---|---|---|---|---|---|---|
| | Heavy sled pull | ES | Back squat | Higher performer | Lower performer | ES | Group ave. |
| Kinetic | | | | | | | |
| Mean anterior GRF (N) | 555 ± 107* (SC to MKE) | 6.63 | 43.0 ± 22.0 (SC to MKE) | – | – | – | – |
| Peak anterior GRF (N) | 810 ± 174* (SC to MKE) | 5.13 | 126 ± 73.0 (SC to MKE) | – | – | – | – |
| Mean vertical GRF (N) | 1330 ± 364* (SC to MKE) | -2.38 | 2580 ± 648 (SC to MKE) | – | – | – | – |
| Peak vertical GRF (N) | 1740 ± 463* (SC to MKE) | -1.85 | 3500 ± 1270 (SC to MKE) | – | – | – | – |
| Mean resultant ant/post force (N) | 271 ± 89.0☼ (MVP) | -1.95 | – | – | – | – | – |
| | 526 ± 162 (AP) | | – | – | – | – | – |
| Mean resultant med/lat force (N) | -5.00 ± 22.0☼ (MVP) | -1.75 | – | – | – | – | – |
| | 24.0 ± 8.00 (AP) | | – | – | – | – | – |

All data is reported as means ± standard deviation, unless specified otherwise. Spatiotemporal and kinematic effect sizes reported for between phase [32] and between performance standard [29], Kinetic effect sizes reported for between exercise (heavy sled pull vs back squat). A positive effect size indicates the left-hand column (higher performer or heavy sled pull) or top row (maximum velocity phase) had a greater value than the respective right-hand column (lower performer or back squat) or bottom row (acceleration phase).* significant difference to back squat, † significant difference to low performing athletes, ☼ significant difference to acceleration phase, *ant/post* anterior/posterior, *AP* acceleration phase, *ave* average, *FS* foot strike, *GRF* ground reaction force, *med/lat* medial/lateral, *MVP* maximum velocity phase, *SC to MKE* start of concentric phase to maximum knee extension, *TO* toe off.

### 3.5.6 STATIC LIFTING EXERCISES

The static lifting strongman exercises biomechanically analysed were the atlas stone lift, log lift and tyre flip. The log lift was the most studied static lifting exercise enabling within and between study comparison (Table 3.5).

#### 3.5.6.1 *BIOMECHANICAL DETERMINANTS OF PERFORMANCE*

The greatest biomechanical determinant of performance in the tyre flip was observed as the second pull phase time (defined as the time between the tyre passing the knee to the hands first leaving the tyre), accounting for ~67% of the between group (HP vs. LP) difference in total tyre flip time [70]. Measures of calf girth, flexed arm girth and total system force (calculated as the sum of the athlete's body mass and 1RM squat) were reported to be the strongest anthropometric determinants of performance in the tyre flip (calf girth: $r = 0.67$; flexed arm girth: $r = 0.66$; total system force: $r = 0.81$) and log lift (calf girth: $r = 0.75$; flexed arm girth: $r = 0.68$; total system force: $r = 0.71$) [6].

#### 3.5.6.2 *WITHIN EXERCISE BIOMECHANICAL DIFFERENCES*

No statistical analysis was performed comparing within exercise (between phase) biomechanical differences in any of the static type strongman lifts.

#### 3.5.6.3 *BETWEEN EXERCISE BIOMECHANICAL DIFFERENCES*

Winwood, et al. [31] compared the biomechanics seen during the clean and jerk (press) movement when using a barbell and a log at a load of 70% of the athlete's barbell clean and press 1RM. Renals, et al. [69] compared the biomechanics seen during the push press when using a barbell and logs of 250 mm and 316 mm diameter at a load of 65% of the athletes' push press 1RM. Greater knee flexion was observed during the start of the second pull phase (deep squat position with log resting on the thighs) of the log clean and press than the equivalent phase of the barbell clean and press, and greater knee and hip extension, and a more vertical trunk position occurred during the top retrieve phase (full standing position with log resting on top of chest) of the log clean and press than the equivalent phase of the barbell clean and press [31]. The increased flexion and extension lead to a greater trunk and hip ROM throughout the entire log clean and press movement than the barbell clean and press movement [31].

Significantly greater mean vertical velocities were reported during the first and second pull phases of the barbell clean and press when compared to the log clean and press, with no significant differences in velocity or dip depth reported during the push press phase using either the barbell or log [31]. Renals, et al. [69] did however report significantly greater vertical propulsive velocity and dip depth when using the barbell than the two different diameter logs during the push press. Braking and propulsive impulse, mean force and mean power were all reported to be significantly greater during the push press when using the barbell than the two logs [69]. Mean posterior force was observed to be significantly greater throughout the entire clean and press movement when using the barbell as opposed to the log [31].

The only reported differences in lumbar joint kinematics during static lifting exercises was greater lateral bend and twist during the tyre flip (lateral bend: ~7°; twist: ~8°) than the log lift (lateral bend: ~3°; twist: ~6°) [36]. When spine angle was normalised to maximum spinal angle, only peak twist (tyre flip: ~109%; log lift: ~68%) was reported to be significantly different [36]. Although no significant differences in muscular and joint loading were reported between the static lifting exercises, anterior core muscle activation (right rectus abdominis, right external oblique) were reportedly greater in the tyre flip than the log lift [36].

Table 3.5 Static lift significant result comparisons.

| | Winwood, et al. [31] | | Renals, et al. [69] | | | McGill, et al. [36] | | Keogh, et al. [70], McGill, et al. [36] |
|---|---|---|---|---|---|---|---|---|
| | 165 mm ø log | Barbell clean and press | 250 mm ø log | 316 mm ø log | Barbell push press | Log lift | Atlas stone | Tyre flip |
| Temporal | | | | | | | | |
| Duration (s) | 7.96 ± 3.77 (TD) | 6.20 ± 1.96 (TD) | 0.22 ± 0.02 (PD) | 0.22 ± 0.02 (PD) | 0.22 ± 0.03 (PD) | – | – | 0.38 ± 0.17 (SP, HP) ☼ |
| | | | 0.67 ± 0.06 (TD) | 0.64 ± 0.07 (TD) | 0.54 ± 0.47 (TD) | | | 1.49 ± 0.92 (SP, LP) |
| Kinematic | | | | | | | | |
| Dip depth (cm) | 17.4 ± 4.40 (PP) | 18.0 ± 6.60 (PP) | 14.0 ± 3.00* (PP) | 13.0 ± 2.00* (PP) | 17.0 ± 4.00 (PP) | – | – | – |
| Vertical lift velocity (m/s) | 0.60 ± 0.10* (FP) | 0.75 ± 0.15 (FP) | – | – | – | – | – | – |
| | 1.06 ± 0.41* (SP) | 1.69 ± 0.15 (SP) | – | – | – | – | – | – |
| | 0.88 ± 0.07 (PP) | 0.97 ± 0.08 (PP) | 0.64 ± 0.07* (PP) | 0.62 ± 0.06* (PP) | 0.74 ± 0.07 (PP) | – | – | – |
| Hip angle (°) | 52.0 ± 6.00* (LO) | 60.0 ± 6.00 (LO) | – | – | – | – | – | – |
| | 182 ± 5.00* (TR) | 158 ± 15.0 (TR) | – | – | – | – | – | – |
| HIP ROM (°) | 126 ± 9.00* (EL) | 116 ± 10.0 (EL) | – | – | – | – | – | – |
| Knee angle (°) | 99.0 ± 25.0* (SSP) | 140 ± 11.0 (SSP) | – | – | – | – | – | – |
| | 139 ± 11.0* (TR) | 125 ± 13.0 (TR) | – | – | – | – | – | – |
| Trunk angle (°) | 106 ± 2.00* (TR) | 91.0 ± 6.00 (TR) | – | – | – | – | – | – |
| | 93.0 ± 5.00* (BD) | 87.0 ± 2.00 (BD) | – | – | – | – | – | – |
| Trunk ROM (°) | 83.0 ± 8.00* (EL) | 67.0 ± 12.0 (EL) | – | – | – | – | – | – |
| Kinetic | | | | | | | | |
| Bra mean force (N) | – | – | 680 ± 262 (PP) | 625 ± 252* (PP) | 775 ± 317 (PP) | – | – | – |
| Bra impulse (N.s) | – | – | 116 ± 28.7* (PP) | 106 ± 27.8* (PP) | 131 ± 27.3 (PP) | – | – | – |
| Bra mean power (W) | – | – | -943 ± 281* (PP) | -854 ± 276* (PP) | -1090 ± 283 (PP) | – | – | – |
| Mean post force (N) | -67.0 ± 14.0* (EL) | -91.0 ± 27.0 (EL) | – | – | – | – | – | – |
| Prop mean force (N) | – | – | 3230 ± 357* (PP) | 3130 ± 363* (PP) | 3400 ± 492 (PP) | – | – | – |

Table 3.5 continued.

| | Winwood, et al. [31] | | Renals, et al. [69] | | | McGill, et al. [36] | | Keogh, et al. [70], McGill, et al. [36] |
|---|---|---|---|---|---|---|---|---|
| | 165 mm ø log | Barbell clean and press | 250 mm ø log | 316 mm ø log | Barbell push press | Log lift | Atlas stone | Tyre flip |
| Kinetic | | | | | | | | |
| Prop impulse (N.s) | 307 ± 56.8 (PP) | 346 ± 66.8 (PP) | 255 ± 38.8* (PP) | 241 ± 28.7* (PP) | 293 ± 40.0 (PP) | – | – | – |
| Prop mean power (W) | 1920 ± 591* (PP) | 2960 ± 802 (PP) | 2040 ± 377* (PP) | 1900 ± 295* (PP) | 2470 ± 482 (PP) | – | – | – |
| Musc ant/post shear (N) | – | – | – | – | – | 2800§ | – | 2600§ |
| Musc comp load (N) | – | – | – | – | – | 7500§ | – | 8800§ |
| Musc ax twist stiff (Nm/rad) | – | – | – | – | – | 25,300§ | – | 31,400§ |
| Musc flex/ext stiff (Nm/rad) | – | – | – | – | – | 32,400§ | – | 38,600§ |
| Muscle activation (%MVC) | | | | | | | | |
| Right rectus abdominis | – | – | – | – | – | 27.3 ± 27.8‡ | 77.6 ± 41.6 | 87.8 ± 63.9† |
| Right external oblique | – | – | – | – | – | 61.5 ± 49.1‡ | 97.6 ± 67.7 | 107 ± 45.4† |

* significant difference to barbell, † significant difference to log lift, ‡ significant difference to tyre flip, ☼ significant difference to lower performing athletes, § value only provided in graph form and as such are approximate values, *ant* anterior, *ax* axial, *BD* bottom of dip, *bra*, braking, *comp* compressive, *EL* entire lift, *flex/ext* flexion/extension, *FP* first pull, *HP* higher performing athlete, *LO* lift off, *LP* lower performing athlete, *musc* muscle, *MVC* maximum voluntary contraction, *post* posterior, *prop* propulsive, *PD* propulsive duration, *PP* push press phase, *SP* second pull, *SSP* start of second pull, *stiff* stiffness, *TD* total lift duration, *TR* top retrieve phase.

## 3.6 DISCUSSION

It can be seen that the field of strongman biomechanics research is relatively small, yet the spread of exercises, biomechanical measures and comparative analysis methods used across current literature is large [12]. As such, it is difficult to establish a comprehensive understanding of the large number of strongman exercises included in the existing literature. Qualitative analysis of these strongman exercises, along with quantitative results from studies of similar TWTE and CEA, may provide a greater understanding of strongman exercise performance determinants, injury risk and wider applications to other populations, while assisting future quantitative analysis of strongman exercises.

### 3.6.1 CARRYING/WALKING EXERCISES

#### 3.6.1.1 *BILATERAL LOAD CARRIAGE*

The farmers walk and yoke walk are the most common bilateral carrying strongman exercises used in strongman training [55]. While both these exercises may involve exceedingly large loads in training and competition, the yoke walk typically involves a greater total load as the limiting factor for farmers walk performance may be the grip strength of the athlete, as in most competitions the only artificial aid athletes can use to assist their grip is lifting chalk. The yoke walk however, has seen little biomechanical analysis, with spinal motion, muscle activation and loading being measured. Although differing in the absolute load and positioning of the load being carried, quantitative analysis of the farmers walk and other forms of load carriage may provide a greater understanding of the biomechanics of the yoke walk strongman exercise. A number of studies have compared various forms of general load carriage to unloaded walking with such studies described in the systematic review [98]. If biomechanical differences between these various forms of load carriage and unloaded walking are consistent across studies (regardless of the form of load being carried), it could be expected that similar biomechanical characteristics are observed in the yoke walk.

A systematic review comparing the biomechanics of backpack load carriage and unloaded walking found backpack load carriage to be associated with an increase in stride rate (ES = 0.37) and a decrease in stride length (ES = –0.32) when compared to unloaded walking [98]. The effect of backpack load carriage on spatiotemporal measures across the studies was small, however effect sizes progressively increased as load increased [98]. Such findings are consistent with the farmers walk strongman exercises where substantially greater loads were used and greater differences when compared to unloaded walking were observed (stride rate: ES = 4.20; stride length: ES = –3.40) [5]. Although a physical limit will be approached whereby the athlete is no longer able to increase their stride rate with a decrease in stride length, it may be expected that the greater loads that can be used in the yoke walk when compared to the farmers walk would result in further increases in stride rate and decreases in stride length. The athlete's ability to maintain/minimise the reduction in their stride length whilst maintaining or increasing their stride rate during the yoke walk will result in a higher velocity and thus a greater performance outcome by the athlete [30].

The greater anterior tilt of the trunk, extension of the knee and dorsiflexion of the ankle observed during the farmers walk when compared to the unloaded walk potentially positions the athlete better to propel themselves in an anterior direction [5]. To achieve an increased stride rate and thus greater velocity (assuming stride length increases or remains constant), ground contact time is typically minimised by greater knee extension throughout the swing phase of a gait cycle.

Significantly greater anterior/posterior, medial/lateral and vertical ground reaction forces were reported during the farmers walk when compared to unloaded walking [5]. Similar results have been reported when comparing backpack load carriage to unloaded walking, where greater propulsive and braking (anterior/posterior), and vertical ground reaction forces were reported during backpack load carriage [98]. The difference in anterior/posterior ground reaction forces seen between unloaded walking and backpack load carriage may partially be the result of the centre of mass of the carrier being pulled backward when the load is positioned posterior to the centreline of the body. Contrary to the farmers walk and unloaded walk comparison, no consistent difference in medial/lateral ground reaction forces have been reported when comparing backpack load carriage to unloaded walking. It may be suggested that the greater medial/lateral ground reaction forces during the farmers walk is the result of both; the load being more laterally positioned relative to the midline of the body in the farmers walk when compared to a backpack, and the substantially greater load being carried in the farmers walk. As such, anterior/posterior and medial/lateral ground reaction forces encountered during the yoke walk may be expected to be even larger than those in the farmers walk due to the greater posterior and lateral positioning of the load relative to the centreline of the body and even greater load being carried.

#### 3.6.1.2 *UNILATERAL LOAD CARRIAGE*

The keg walk and suitcase carry unilateral load carriage strongman exercises are not common strongman competition events and perhaps as a result have had little biomechanical analysis [36, 55, 97].

The keg walk technique adopted in McGill, et al. [36] whereby the keg is carried on a single shoulder is just one technique which may be used by an athlete in a keg walk competition event or as a strength training exercise for non-strongman athletes. Other techniques to perform the keg walk may include: wrapping one's arms around the keg in a hugged position on the anterior surface of their abdomen; lifting and carrying the keg using the handles positioned around the rim of the keg; or a combination of the aforementioned techniques. Individualised biomechanical analysis of each technique would therefore be required and as such is beyond the scope of this review. It may however be expected that these techniques see some biomechanical similarity to anterior load carriage [99], manual handling of beer kegs [100], and to some degree the carrying of a kettlebell in a bottom up position where the humerus is externally rotated and horizontally abducted [101].

Performance in the suitcase carry has been characterised by an athlete's ability to maintain a vertical spinal posture (with respect to the frontal and sagittal anatomical plane) and a constant step cadence [97]. This may be deduced by the tendency for an increase in lateral bend and inability to maintain a set cadence as load is progressively increased [97]. Similar studies of unilateral load carriage of a 20% body mass dumbbell has shown increased trunk bend, hip adduction and ground reaction force asymmetry, and decreased stride width when compared to a 10% body mass dumbbell and unloaded walking conditions [102]. As the load used in previous suitcase (McGill, et al.: ~ 31% bodyweight; Holmstrup, et al.: ~ 63% bodyweight) and unilateral dumbbell carriage studies may be less than what is expected to be used in strongman training; trunk bend, lumbar spinal loading, ground reaction force asymmetry, and changes in gait characteristics may be further magnified in a true strongman setting where greater loads are carried.

The results of future research on the biomechanics of strongman carrying/walking type exercises may assist in determining the biomechanical demands of military physical fitness assessment exercises such as the jerry can carry which is used to assess dynamic and grip strength, whereby military personnel carry jerry cans (usually of mass > 20 kg) a short distance (~ 20 m) in the fastest possible time [103]. As the practical guidelines on how to best condition soldiers for load carriage is limited, findings from strongman research may play a pivotal role in this formation [104]. Similarly, research into the biomechanical demands of other bilateral strongman load carriage exercises such as the yoke walk may provide a foundation for further research into the demands placed on firefighters carrying breathing apparatus and firefighting equipment, and trail porters who have been known to carry loads of one-and-a-half times their body mass over vast distances [105].

### 3.6.2 PULLING EXERCISES

Previous strongman biomechanical studies have only analysed the biomechanics of athletes performing the heavy sled pull (>100% body mass), which is typically used as a training tool to simulate the vehicle pull for strongman athletes, or as a strength and conditioning tool for other athletic groups [29, 32]. In addition to the heavy sled/vehicle pull, strength and conditioning coaches often use a variety of similar resistive sprint training tools for the development of greater horizontal force production and sprinting ability in athletes [106, 107]. Such tools may include weighted vests, tyres and parachutes. A study comparing the biomechanics of athletes performing the sub-body mass sled pull, parachute pull and weighted vest run to unloaded sprinting has shown the sub-body mass sled pull (performed with a metal tubular sled on a synthetic running track loaded to ~16% body mass) to result in the greatest decreases in velocity, stride length and stride frequency, and increase in trunk lean angle when compared to unloaded sprinting [107]. The more horizontal trunk position attained by the athlete when performing the sub-body mass sled pull may indicate that the sub-body mass sled pull has greater biomechanical similarity to the heavy sled pull and thus the strongman vehicle pull than the parachute pull and weighted vest run.

Although few studies have assessed the biomechanics of athletes performing pulling movements representative of a vehicle pull at loads greater than 100% body mass, a number of studies have compared biomechanical measurements between athletes performing a sub-body mass sled pull at varying loads [108-111]. Extrapolating the results of studies comparing the biomechanics of athletes performing sub-body mass sled pulls at different loading conditions may assist researchers, strongman athletes and coaches, and strength and conditioning coaches better understand the biomechanics that may be expected in the strongman vehicle pull where resistive loads much greater than body mass are seen.

Greater decreases in velocity, stride length and second-stride swing time, and greater increases in ground contact time have been found to occur when performing a sub-body mass sled pull at a sled load of 32.2% body mass compared to 12.6% body mass [108]. While no significant difference in stride rate was reported between the two sub-body mass loading conditions, stride rate was significantly lower under both loading conditions than the unloaded condition [108]. Although no comparisons between loading conditions were made in the heavy sled pull study of Keogh, et al. [29], similar changes in spatiotemporal parameters may be deduced from the lower velocity trials, whereby a reduced stride length and swing time, and increased ground contact time were reported [29].

When comparing joint kinematics between unloaded sprinting, sled pulls at 15%, 20%, 30% and 40% body mass, significant increases in knee and hip flexion at foot-strike and toe-off have been reported with an increase in sled load [109]. The greater knee and hip flexion at foot strike and toe off would likely result in the athlete attaining a more horizontal trunk position throughout the pull. Where the increases in sled mass in the study by Monte, et al. [109] were associated with a decreased pull velocity, lower velocity during the heavy sled pull in Keogh, et al. [29] and Winwood, et al. [32] was similarly characterised by a more horizontal trunk position and greater knee flexion at foot strike. Qualitatively, it may appear that the more horizontal trunk orientation is a mechanism employed by the athlete to position the body so to optimise horizontal propulsive force production, however more quantitative research is required to confirm this hypothesis.

The direction of the resultant ground reaction force of the athlete when performing the sled pull and strongman vehicle pull may however also be dependent on the location at which the load is applied on the athlete's body. Utilising a waist attachment site instead of a shoulder height attachment site on the athlete has been observed to result in the athlete attaining a more horizontal body position [112]. This is achieved through a greater trunk ROM and greater peak knee flexion during the stance phase of the sled pull [112]. The use of such an attachment site may increase the athlete's ability to impart a horizontally directed propulsive impulse on the sled [112]. Although the vehicle pull strongman event is typically performed using a chest harness which sees an attachment site somewhere between the shoulder and the waist, a qualitative analysis of the strongman vehicle pull shows a similar minimal tow rope angle relative to horizontal due to the high attachment point of the rope on the vehicle. Thus, the vehicle pull may see a similar direction of force application to a loaded sled pull performed with a waist level attachment site.

From existing literature comparing the biomechanics of athletes performing sub-body mass sled pulls at varying loads, and the limited literature available on the heavy sled pull strongman exercise, it may be deduced that decreases in stride length and stride rate and increased trunk lean may be further magnified in the strongman vehicle pull where an increased resistive load is expected. Furthermore, based on this knowledge and the relationship between increased sled load and decreased pulling velocity, it may be hypothesised that greater performance in the strongman vehicle pull competition event could be characterised by the athlete's ability to maintain a greater cadence and stride length, whilst attaining a trunk position that enables greatest horizontal force production throughout the pull.

The current heavy sled pull research may be used as a basis for further research into the biomechanical demands of performing other variations of the heavy sled pull such as the backward drag, and the vehicle pull. The backward drag technique is used in firefighting and military physical fitness assessments and service, where service people may be required to drag victims out of danger [113, 114]. Further investigation into the biomechanical demands of a vehicle pull may be of benefit to military operations, as soldiers may be faced with instances where they are required to pull/push heavy equipment over short distances [114].

### 3.6.3 STATIC LIFTING EXERCISES

A significant lack of quantitative biomechanical analysis exists on the atlas stone lift, log lift and tyre flip. To qualitatively analyse these three exercises, they may be broken down into phases and biomechanically analysed alongside a variety of different TWTE and CEA.

#### 3.6.3.1 *ATLAS STONE LIFT*

Of the three static strongman lifts analysed in the current literature, the atlas stone may be seen as one of the most mechanically demanding and potentially injurious strongman exercises [14]. Quantitatively, the atlas stone lift has seen limited biomechanical analysis, with just joint/muscle loading and muscle activation being measured [36]. To provide greater insight into the biomechanics of the atlas stone lift, the lift may be qualitatively divided into three distinct phases, with each phase showing biomechanical similarity to individual TWTE and CEA.

Phase one of the atlas stone lift generally sees the athlete hug the stone prior to attempting to lift it off the ground using a technique similar to a Romanian deadlift, before assuming a paused position with the stone resting in the lap similar to the end of the first phase of the log lift. Limited research exists for similar TWTE or CEA. The most similar and comprehensive field of research related to the biomechanics of this movement is in the area of injury risk assessment/prevention for the manual handling stoop lifting technique, which is characterised by a bent back and straight knee posture until lift completion (fully erect standing position) [115]. Net moments and compressive forces acting on the spine have been reported to be similar between the stoop lifting technique and the often preferred squat lifting technique (characterised by a straight back and bent knee posture until lift completion) [115]. The insignificant differences in joint loading between these lifting techniques is supported by the findings of McGill, et al. [36] where vertebral joint moments, muscular/joint compression and shear forces during the atlas stone lift were reported to be of a similar or lower magnitude to other strongman exercises analysed including the farmers walk, yoke walk, keg walk and log lift. The limited research on a similar movement to phase one of the atlas stone lift justifies further research to progress the performance of athletes undertaking this exercise, whist also being of benefit to the understanding of manual handling tasks.

Phase two of the atlas stone lift sees the athlete paused with the stone resting in the lap in a deep squat position. The athlete may rest in this position for a short period of time to reposition their hands before beginning the third phase. A qualitative analysis of the atlas stone lift shows that the second phase of the lift may see biomechanical similarity with the beginning of the concentric phase of a box squat whereby in each exercise there is a period of ‘rest’ where the lower limb muscles are expected to see a significant reduction in activation. A significantly smaller trunk angle relative to the normal vertical axis has been reported at this point during the box squat (26.9°) than the same stage during the traditional (33.5°) or powerlifting (33.1°) style squat [79]. The more vertical trunk position in the box squat also corresponded to a reduced L5/S1 joint moment [79]. Although not calculated at precisely the same vertebral joint, the L4/L5 joint moments measured during the atlas stone lift (183 ± 177 N.m) [36] appeared to be similar or slightly less than the L5/S1 joint moments in the box squat (233 ± 21.0 N.m) [79]. Under similar loading conditions (box squat: ~110 kg; atlas stone lift: 110 kg) this difference may indicate that during the second phase of the atlas stone lift a similar or even smaller trunk angle relative to the vertical axis may be seen, thus perhaps exposing the athlete to a lower risk of lower back injury.

The explosive movement initiated from the end of phase two to the early stages of phase three of the atlas stone lift may be most similar to that of the beginning of the concentric phase of the box squat [79]. The box squat has been reported to result in significantly lower peak force production than the powerlifting or traditional style squat (box squat: 2528 ± 302; powerlifting: 2685 ± 301; traditional squat: 2680 ± 309 N) [79]. This was suggested to be due to the pause and transfer of load from the system to the box at the bottom of the squat, meaning the box squat may lose some of the benefits of the stretch-shorten cycle in terms of force production and loads lifted. There was however a significantly greater rate of force development in the box squat compared to the traditional and powerlifting style squats [79]. It may be expected that increasing a strongman athlete's ability to utilise the stretch shorten cycle at the bottom of the atlas stone lift, whilst also promoting a high rate of force development, may be key in achieving greater performance in the atlas stone lift. This may be achieved by including exercises such as barbell back squats, front squats and Zercher squats for the training of greater stretch-shorten cycle utilisation, while barbell box squats and Zercher squats from a low rack may be included for the training of greater concentric rate of force development.

Phase three of the atlas stone lift sees the athlete move with the stone from the bottom of the squat position to a full extension standing position, with the stone being transferred to a chest height ledge or over a bar. This final stage of the atlas stone lift may show biomechanical similarity to the concentric phase of the front squat whereby the load is lifted in a squat like position on the anterior surface of the body to a full extension standing position. Comparative analysis of trunk angle kinematics of the front squat and back squat have reported the positioning of the load on the anterior surface of the body to result in a more vertical trunk position at the beginning of the concentric phase of the squat (front squat: 27°; back squat 43°) [116]. Whilst still being in a flexed torso position throughout the entirety of the front squat, the atlas stone lift often sees the athlete move into a position of torso extension during the final stage of the lift where the stone is passed onto the ledge/over the bar. The degree of movement of the torso into an extended state may be expected to differ between athletes of varying anthropometrics and performance standard, and may see unique muscular and joint loading. Further quantitative analysis of the atlas stone lift is required to confirm this hypothesis.

The inclusion of the atlas stone lift into a strength and conditioning program may be of interest to military personnel or civilians required to perform physical lifting fitness assessments. Such an example of this form of test is the box lift and place assessment conducted in the Australian Army, whereby a box (up to 40 kg) must be lifted from the ground and placed on a ledge of height 1.5 m [117]. It has been suggested that this and similar repetition based box lift and place tasks may be a more appropriate means of assessing an individual's ability to perform military specific tasks than a generic push-up or sit-up test [118].

#### 3.6.3.2 *LOG LIFT*

The log lift is commonly used by strength and conditioning coaches as an alternative to other overhead lift variations and has seen substantial biomechanical analysis [7, 31, 36, 69]. There however remains a gap in the current strongman literature identifying the biomechanical determinants of greater performance in the log lift exercise. Furthermore, literature on the biomechanical determinants of performance in all forms of strength based overhead pressing exercises is lacking. As such, the advancement of researchers' understandings of the biomechanical determinants of performance in the log lift is limited to phase one and two of the movement which is representative of the power clean [31].

One repetition maximum in the power clean has been reported to show strong correlation to the combination of decreased hip ROM during the first pull phase of the lift and a rapid extension of the hip during the second pull phase ($r = 0.87$) [80]. Qualitatively, this may be representative of what is commonly seen in the log lift, whereby athletes lifting close to their 1RM will typically sink down into a deep squat position during phase one of the lift with large hip and knee flexion, concluding the phase in a paused position with the log resting in their lap. The athlete will then move into phase two of the lift where an attempt is made to perform a rapid hip extension so to move the log at a high velocity before catching and racking the log on their chest. An athlete's ability to execute the clean with minimal hip flexion during phase one and perform a powerful hip extension during phase two of the log lift is particularly evident in log lift competition events that require athletes to perform as many repetitions as possible in an allocated time at sub-maximal loads. Greater performance (achievement of a successful lift at a greater barbell load) in the power clean has also been characterised by an athlete's ability to keep the barbell close to their body throughout the second pull phase of the lift (likely through a greater net force application toward the body) [119]. This is likely to have great applicability to the log lift as the increased diameter of the log is expected to make achieving greater net force application toward the body more difficult due to the centre of mass of the log being positioned further in front of the centre of mass of the athlete.

#### 3.6.3.3 *TYRE FLIP*

Although the tyre flip is commonly used as a strength and conditioning training tool at a recreational and elite sporting level [7], biomechanical analysis of the exercise has only considered temporal determinants of greater performance [70]. Biomechanical analysis of the tyre flip exercise may be particularly difficult as the lift is one of the few strongman lifts where the implement remains in contact with the ground throughout the entirety of the lift, thus quantifying the load lifted by the athlete may be difficult. Additionally, the dimensions as well as the mass of the tyre is likely to have an impact on the technique/biomechanics of the athlete performing the lift. The following qualitative analysis of the tyre flip is of a general case which may be most commonly observed. Qualitatively, aspects of the tyre flip exercise may share some biomechanical similarity to phases of the deadlift and power clean/clean and jerk, thus some degree of transferability of the biomechanical performance determinants, expected training adaptations, and injury risks and prevention mechanisms may exist between these exercises.

Phase one of the tyre flip sees the athlete begin the movement by lifting one side of the tyre off the ground to a knee height position. This would appear to be biomechanically similar to the aspects of the initial lifting phase of the conventional and sumo deadlift, whereby a combination of distinct characteristics from each deadlift technique is likely to be adopted in the execution of the tyre flip, depending on the athlete, tyre and surface characteristics. Escamilla, et al. [34] compared joint/segment angular kinematic measures between the sumo and conventional deadlift, reporting athletes implementing the sumo style technique had a more vertical trunk orientation (33.0 ± 11.0°) than those implementing the conventional style technique (24.0 ± 10.0°). From a qualitative analysis of trunk angle kinematics during the initial lift phase of the tyre flip it may appear that the tyre flip exhibits greater biomechanical similarity to the conventional deadlift during this phase due to the more horizontal trunk position. Conversely, the significantly greater stance width displayed by athletes implementing the sumo technique (sumo: 70.0 ± 11.0 cm; conventional: 32.0 ± 8.00 cm) may be more representative of the tyre flip stance at lift off. Phase one of the tyre flip appears to share some characteristics of both the sumo and conventional deadlift, however further quantitative analysis is required to confirm these observations.

The second pull phase of the tyre flip sees the athlete continue the lift of the tyre from the knee height position to first hand release where the tyre may be close to a 75° angle from horizontal. This phase of the tyre flip shows biomechanical similarity to the power clean whereby powerful triple extension of the ankle, knee and hip are required to move the bar from mid-thigh (hang) to the catch position (top of the chest). The second pull phase has been identified as a key biomechanical determinant of performance in the tyre flip, with the greatest differences between the fastest and slowest athletes/repetitions observed during this phase [70].

The second pull phase of the power clean has also been reported to contain key biomechanical determinants of performance [119]. Comparing successful versus unsuccessful attempts of the power clean revealed that greater performance may be characterised by an athlete's ability to minimise forward barbell displacement during the second pull phase of the lift [119]. It is expected that the reduced forward barbell displacement relative to the centreline of the body minimises the resistive joint torques experienced by the athlete and thus ensures maximal vertical force production. The second pull phase of the tyre flip sees the athlete move their body toward the tyre and maintain or further advance their body position relative to the tyre. Similar to the second pull phase of the power clean the athlete's ability to reposition their body segments in relation to the load during the second pull phase of the tyre flip for optimal force production will likely have a large effect on the overall performance outcome of the flip.

The third phase of the tyre flip sees the athlete catch the tyre on the chest by attaining a position of full extension of the wrist and hand, pronation of the forearm, flexion of the elbow and extension of the shoulder, before powerfully pushing the tyre past its tipping point. Qualitatively, this motion generally occurs at around chest to shoulder height depending on the dimension of the tyre and the anthropometrics and technique of the athlete. The motion involved with phase three of the tyre flip may be biomechanically similar to pushing a loaded cart.

Al-Eisawi, et al. [120] investigated the forces required to initiate movement of a loaded cart (up to 181 kg) equipped with 152 mm diameter wheels on a level, carpeted surface, from different vertical positions (knuckle, elbow, shoulder height). It was reported that as the height at which the cart was pushed increased, the applied horizontal (anterior) force decreased and the vertical force component transitioned from a negatively (downward) applied force to a positively (upward) applied force [120]. As the tyre flip is performed as a tipping motion as opposed to a rolling/translational motion, the combination of horizontal and vertical force components applied to the tyre would see significant importance in the assessment of the performance outcome of the flip. While the first two phases of the flip are expected to require a significant vertical force component, it is expected that as the flip progresses to the third phase, the requirement of a greater horizontal force component becomes apparent. Thus, although the results of Al-Eisawi, et al. [120] saw a decrease in horizontal force application at greater heights, this may not be directly representative of what is seen in the tyre flip.

Future researchers may attempt to quantify this qualitative assessment, along with the biomechanical differences which occur as a result of performing the tyre flip with different dimension tyres, and the likely training benefits, performance determinants and injury risks associated with each tyre dimension.

## 3.7 CONCLUSION

The collation, assessment and interpretation of the results from the eleven identified strongman biomechanics studies has outlined the current understanding of the biomechanical determinants and applications of strongman exercises. Qualitative assessment of the eight strongman exercises, and comparison to quantitative biomechanical data of TWTE and CEA were used to develop further potential insights into the determinants of strongman exercise performance and applications of strongman exercises outside of the sport of strongman. A lack of quantitative biomechanical data was identified in the areas of: a basic biomechanical analysis of the yoke walk, unilateral load carriage exercises, vehicle pull, atlas stone lift and tyre flip; and more specific biomechanical performance determinants of the log lift exercise. Future research in the identified areas of strongman biomechanics is expected to provide a greater understanding of the biomechanical determinants of performance in a wider range of strongman exercises, and the potential training adaptations and risks expected when performing and/or incorporating strongman exercises into strength and conditioning or injury rehabilitation programs. This review has demonstrated the likely applicability and benefit of current and future strongman exercise biomechanics research to: strongman athletes and coaches; strength and conditioning coaches considering using strongman exercises in a training program; and tactical operators (e.g. military, army) and other manual labour occupations.

# CHAPTER 4:

# RESEARCH METHODOLOGY OVERVIEW

# 4. Research Methodology Overview

This chapter provides an overview of the research methodologies used throughout the thesis and rationale for the decisions made in the design of the experimental study protocols and measurement device selection.

## 4.1 Strongman biomechanics experimental protocols

The experimental protocols of previous strongman biomechanics research were summarised in Systematic Review 1. The relevance of the carry distances, loads and repetition ranges used in previous research to actual strongman training practices was still, however, unclear. With the exception of a study by Winwood, et al. [55], which provided a general overview of the strength and conditioning practices of strongman athletes, a lack of literature exists on the specific training practices of strongman athletes for each strongman exercise. The lack of information on distances, loads and repetition ranges used by strongman athletes for specific exercises resulted in the researcher further consulting with three individuals from outside the supervision team to determine some of the exact methods for the experimental studies described in Chapter 7 and Chapter 8. This group of individuals, who will be referred to as "the strongman coaching panel" from here forth were:

- Jean-Stephen Coraboeuf, professional strongman, international/national level strongman coach and 2019 Australia's Strongest Man;
- Colin Webb, international/national level strongman coach; and
- Greg Nuckols, international/national level strongman coach.

The results of Systematic Review 1 and Systematic Review 2, combined with results of Winwood, et al. [55], which identified the most commonly trained strongman exercises, was used to establish a list of the four most commonly trained strongman exercises lacking basic quantitative biomechanical analysis. These exercises were the yoke walk, vehicle pull, atlas stone lift and tyre flip. From discussions held with Jean-Stephen Coraboeuf, the yoke walk and atlas stone lift were selected for the biomechanical analysis component of the PhD project. The yoke walk and atlas stone lift were selected to ensure the greatest impact and practical applicability of the PhD research output to strongman athletes, coaches and strength and conditioning coaches.

Athlete performance in a strongman competition event can be determined in a variety of ways in both the yoke walk and atlas stone lift, as such, challenges in establishing an ecologically valid testing protocol arose. In the case of the yoke walk, the load and distance/duration stipulated to be carried by athletes will vary from competition to competition, with this variation typically reflective of the sex and body mass of the athlete. For example, athletes might be required to carry a heavier load (light-weight females: 150 kg; heavy-weight males: 300+ kg) a distance of 20 m or less in one competition, while in another competition athletes might be required to carry a relatively lighter load (light-weight females: 120 kg; heavy-weight males: 280 kg) a longer distance of 40 m.

Even greater variance in competition loading may be seen for the atlas stone lift where loading can vary depending on the height to which the stone is to be lifted (e.g., 1 to > 1.3 m, with lower heights typically used for female classes), the number of lifts to be performed (e.g., one repetition maximum (1RM), set number of stones, or as many repetitions as possible (AMRAP)), the sex of the athlete and the body mass classes offered within the federation or competition. The mass of the stone may also vary within the set where multiple repetitions are performed (e.g., light-weight female stone series: 50, 60, 70, 80, 90 kg; heavy-weight male stone series: 120, 140, 160, 180, 200 kg). Further variance in an atlas stone competition event can be seen as a result of the stone surface finish and diameter, with the majority of stones having somewhat unique characteristics. Loading schemes based on previous strongman competition rules for each sex and body mass class were considered as a possible way of establishing testing protocols for both the yoke walk and atlas stone lift. Competition-based loading schemes would provide a direct representation of the biomechanics of athletes which may be expected under competition conditions.

Specifying data collection protocols based on actual competition load and repetition schemes was, however, considered to put athletes participating in the study at unnecessary risk of injury, as athletes typically do not maintain competition performance levels for all strongman exercises all year round [54]. Asking athletes to undertake a training block of 8 – 12 weeks in preparation for two single testing sessions was expected to result in a significant decrease in the number of participants recruited for each study. From discussions with the strongman coaching panel, data collection protocols were established for each of the yoke walk and atlas stone lift to ensure:

1) the risk of injury to athletes was minimised;

2) a high level of ecological validity of the results to training performance was maintained; and

3) the greatest number of experienced male and female strongman athletes were recruited.

A two-part testing protocol was established for both the yoke walk and atlas stone lift.

#### 4.1.1 Yoke walk protocol

Part one of the yoke walk protocol (see Chapter 7 for additional details on both part one and part two) consisted of a pre-test 1RM whereby athletes were required to carry a maximal load a distance of 20 m in under 20 seconds without dropping the yoke. A distance of 20 m was selected, as it was considered to be a medium distance where athletes would carry a moderate to heavy load and the most common format of the yoke walk encountered in competition. The requirement to complete the set within 20 s and with no drops was established as a cut-off for failure, whereby athletes dropping the yoke or completing the set outside of 20 s would be unlikely to position highly in a competition of distance-for-shortest-time format.

Part two of the yoke walk protocol was completed one week later and required athletes to complete three sets of a 20 m yoke walk at 85% of their previously defined 1RM 20 m yoke walk load. A loading of 85% 1RM was used to allow athletes to perform three maximal effort sets with high velocity and no drops, replicating how athletes may practice the yoke walk in a training session in preparation for a competition. Recovery periods between each set for both part one and part two of the yoke walk protocol were established based on previous literature on the strength and conditioning practices of strongman athletes [55].

#### 4.1.2 Atlas stone protocol

Part one of the atlas stone protocol (see Chapter 8 for additional details on both part one and part two) consisted of a pre-test 1RM whereby athletes were required to lift a maximal load stone over a set height bar commonly used in competitions (male: 1.3 m; female: 1.2 m). The set height bar is a common competition format.

The format of the atlas stone protocol presented a particular challenge, in that, submaximal atlas stone competition events are often either performed as an AMRAP set of a constant mass stone, or as a set of a specific number of stones of incremental mass (for the fastest time). Using an AMRAP format would result in variability due to declining performance with fatigue, increased chance of failure and a varying number of repetitions performed by athletes. An incremental mass format would result in variability due to declining performance with fatigue and the varying mass and dimension of the stone. The challenges associated with standardising both failure and an uneven number of repetitions between participants in an AMRAP format, led to the decision to use an incremental mass format for part two of the atlas stone protocol.

Defining loads for the set of stones of incremental mass also presented as a challenge. Guidance from the strongman coaching panel was relied upon heavily in defining incremental loading to ensure athletes would be somewhat challenged by the first stone mass in the set, but still be able to complete the final stone in the set. The availability of stone masses at the testing sites that would be suitable for potential participants also had to be considered when selecting loading conditions.

Part two of the atlas stone protocol required athletes to complete three sets of four stones of incremental mass (stone one ≈ 60% 1RM, stone two ≈ 70% 1RM, stone three ≈ 80% 1RM, stone four ≈ 85% 1RM) over a fixed height bar (as per the height in part one). These percentages of 1RM were thought to be reflective of the training practices of the strongman coaching panels' athletes when performing incremental mass stone lifting. As per the yoke walk protocols, part two was completed a week after part one and recovery periods between each set were established based on previous literature on the strength and conditioning practices of strongman athletes [55].

#### 4.1.3 ADDITIONAL PROTOCOL CONSIDERATIONS

The use of lifting aids (including lifting belts and knee/elbow sleeves) by athletes undertaking testing protocols was identified as a potential cofounding factor in the results. It was suggested that providing athletes with the option to use lifting aids when undertaking the testing protocol may introduce greater variance in the results, as some athletes may choose to use lifting aids while others may not. Intentionally reducing this variance in the results by prohibiting the use of all lifting aids, may however, compromise the ecological validity of the results as well as place athletes at greater risk of injury by asking them to perform exercises in a way in which they would not regularly be performed. The majority of competitions allow lifting belts, knee/elbow/forearm sleeves and tacky to be used for the atlas stone lift, while lifting belts, knee/elbow sleeves and chalk may be used for the yoke walk. These lifting aids are generally also used by athletes during training [72] and as such, were permitted for use during testing protocols in accordance with the respective competition rules for each exercise.

## 4.2 Inertial motion capture device selection

In conducting Systematic Review 1, the limitations associated with the use of traditional motion capture methods to analyse the biomechanics of athletes performing strongman exercises were identified. Inertial motion capture (IMC) was selected as the most suitable motion capture method to overcome many of the limitations associated with the use of traditional motion capture methods to analyse the selected strongman exercises in the PhD project, whilst fitting within PhD budget constraints.

Generally, IMC can be implemented using "out of the box" commercial systems whereby researchers can purchase the IMC system, place the sensors on the body of a participant and obtain relatively immediate biomechanical measures. Commercial "out of the box" IMC systems can, however, be expensive [121], and still require validation against a gold standard method, as the intended purpose of many commercial IMC systems is for gaming and animation [122]. Where the validity of results obtained using a commercial IMC system are insufficient, the researcher is limited in their ability to tune or improve the agreement between systems due to the proprietary software often used in commercial IMC systems. Additionally, commercially available IMC systems designed for clinical applications may only measure a subset of the biomechanical parameters desired by the researcher.

Building an IMC system from individual components, which may include multiple inertial measurement unit (IMU)/magnetic angular rate and gravity (MARG) sensors, a BlueTooth module, an Arduino microcontroller and a battery pack, provides an inexpensive means of collecting the raw data which can be used to estimate the same biomechanical measures as a commercial IMC system [123]. Specialised data processing methods are then implemented by the researcher to obtain the desired biomechanical measures, allowing for the accuracy of the system to be tuned by the researcher.

Purchasing relatively inexpensive commercially available IMU/MARG devices which already include the mentioned componentry is a middle ground between a commercially available "out of the box" IMC systems and a component-built system. Raw data from commercially available IMU/MARG devices can be processed by the researcher (as per the component-built system) to estimate biomechanical measures.

For the purpose of the PhD project and to allow potential re-use of the devices for various applications in future research within the university, it was decided that the commercially available IMeasureU Blue Trident (ImeasureU, Vicon Motion Systems Ltd., Oxford, UK) MARG device would be used to collect the raw data for further processing and biomechanical analysis by the researcher. The IMeasureU Blue Trident was selected as it includes a high-rate accelerometer, gyroscope and magnetometer within a waterproof housing, with between-device synchronisation and onboard or to-device data collection capabilities. Further details on the rationale behind the selection of data processing methodologies used to estimate the desired biomechanical measures from the raw data obtained from the IMeasureU Blue Trident MARG will be provided in subsequent chapters.

# CHAPTER 5:

# TECHNICAL SUMMARY LITERATURE REVIEW

# 5. Inertial-based human motion capture: a technical summary of current processing methodologies for spatiotemporal and kinematic measures

## 5.1 Preface

A common theme identified in Chapter 2 was the use of 2D video motion capture (VMC) for the measurement of spatiotemporal and joint kinematic parameters of athletes performing strongman exercises. The use of 2D VMC and other forms of traditional motion capture was suggested to limit the ability of previous researchers to analyse the biomechanics of athletes performing some strongman exercises. It was concluded that inertial motion capture (IMC) may be used to overcome some of these limitations. Prior to addressing the strongman-specific component of Question 3 *"How may current inertial motion capture methods be used and further developed to characterise the biomechanics of athletes performing strongman exercises?"*, this chapter details the current IMC data processing methodologies used to estimate spatiotemporal and kinematic parameters in the wider areas of sporting and clinical applications. The understanding gained by critically reading the IMC literature and synthesising it within this chapter was used to inform the methodologies selected for use within the validation and two experimental chapters that follow within this thesis.

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## 5.2 Abstract

Inertial motion capture (IMC) has been suggested to overcome many of the limitations of traditional motion capture systems. The validity of IMC is, however, suggested to be dependent on the methodologies used to process the raw data collected by the inertial device. The aim of this technical summary is to provide researchers and developers with a starting point from which to further develop the current IMC data processing methodologies used to estimate human spatiotemporal and kinematic measures. The main workflow pertaining to the estimation of spatiotemporal and kinematic measures was presented and a general overview of previous methodologies used for each stage of data processing was provided. For the estimation of spatiotemporal measures, which includes stride length, stride rate and stance/swing duration, measurement thresholding and zero-velocity update approaches were discussed as the most common methodologies used to estimate such measures. The methodologies used for the estimation of joint kinematics were found to be broad, with the combination of Kalman filtering or complementary filtering and various sensor to segment alignment techniques including anatomical alignment, static calibration and functional calibration methods identified as being most common. The effect of soft tissue artefacts, device placement, biomechanical modelling methods and ferromagnetic interference within the environment, on the accuracy and validity of IMC was also discussed. Where a range of methods have previously been used to estimate human spatiotemporal and kinematic measures, further development is required to reduce estimation errors, improve the validity of spatiotemporal and kinematic estimations and standardise data processing practices. It is anticipated that this technical summary will reduce the time researchers and developers require to establish the fundamental methodological components of IMC prior to commencing further development of IMC methodologies, thus increasing the rate of development and utilisation of IMC.

## 5.3 INTRODUCTION

Motion capture systems have been used extensively in biomechanics research to capture spatiotemporal measures of stride length, stride rate, contact time and swing time and angular kinematic measures of joint angles. Such measures are commonly used in disease/condition diagnosis, injury prevention and sport performance analysis [43, 44, 47, 124-127]. The most common technologies used to collect human spatiotemporal and kinematic measures are three-dimensional (3D) optical, two-dimensional (2D) video, and electromagnetic based systems [15]. When motion capture data is collected in conjunction with data from force platforms, angular kinetics may also be modelled.

Three-dimensional optical motion capture (OMC) systems are often considered to be the gold standard method of motion capture, however these systems are expensive and typically confined to a small capture volume within a laboratory environment [16, 24]. For a full body motion analysis, researchers are required to place up to 50 markers at anatomically specific locations, and a line of sight to each marker must be maintained by at least two cameras for each data frame throughout the movement [16]. Maintaining a line of sight to each marker throughout the movement is a major challenge when using 3D OMC as markers often become displaced and/or occluded when implements (such as boxes for manual handling assessments, and bats, balls or barbells for sporting assessments) are included in the movement analysis [16]. The displacement and/or occlusion of markers result in loss of data, increased measurement error, increased tracking time and sometimes the inability to analyse a captured movement.

Two-dimensional video motion capture is a more affordable alternative to 3D OMC, requiring one or more video cameras with sufficient frame rate, and video processing software such as the freely available software Kinovea (Kinovea.org, France) or Tracker (Open Source Physics). A number of drawbacks exist for 2D video motion capture. Multiple video cameras may be required for a full motional analysis. For example, for a running gait motion analysis, cameras may be required with views of the frontal and sagittal plane to capture joint varus/vulgus rotation, and joint flexion/extension, stride length, stance duration and swing duration, respectively. The high frame rate required to ensure accuracy when capturing fast movements (particularly sporting movements) result in large file sizes and extensive processing time. Both marker-based and marker-less 2D video motion capture rely on a line of sight of the participant throughout the movement and as such see similar occlusion limitations to 3D OMC [16]. Parallax error caused by the participant performing the movement at a non-perpendicular angle (out of plane) to the camera, and perspective error caused by the participant moving toward or away from the camera are additional sources of error when using 2D video motion capture [26, 34].

Electromagnetic motion capture requires the participant to wear a specially designed suit of electromagnetic receiver sensors which receive electromagnetic waves from a base station transmitter located within the vicinity of where the movement is to be performed [15]. The receiver/transmitter network allows the position and orientation of the body to which the receiver sensors are attached to be determined within space [15]. Electromagnetic motion capture systems do not rely on line of sight measurements and thus do not encounter the problems of marker displacement and/or occlusion when implements are included in the motion analysis [15]. Low sampling rates currently make electromagnetic motion capture systems unsuitable for fast movements [15]. Motion capture often takes place at laboratory, clinical or sporting facilities where equipment in the environment emit electromagnetic disturbance. Electromagnetic motion capture systems are susceptible to electromagnetic interference from the surrounding environment, causing potentially large errors in orientation estimations [15].

While each of these traditional motion capture methodologies have their own advantages and disadvantages, no single method is appropriate for all applications. Recent developments in inertial measurement unit (IMU) and magnetic, angular rate and gravity (MARG) sensor technologies have resulted in researchers proposing the use of such devices to overcome many of the limitations of traditional motion capture systems, particularly when data needs to be collected outside of a laboratory.

Inertial devices have been used for human motion capture in the areas of athlete external load monitoring [128-130], activity classification [131-135], and spatiotemporal and kinematic analysis [43, 47, 127, 136]. The methodology of external load monitoring using inertial devices uses the raw output data of the IMU/MARG device (often accelerations) and thresholding techniques to determine the amount of exposure an athlete may have to various magnitudes of acceleration (external load) over the course of a training session, game/competition or other relevant period of time such as a week, month or year [130]. Such data is typically used to provide some insight into athlete performance, training adaptation, fatigue and risk of injury [130]. Activity classification is used to identify movement patterns such as walking, running, stair ascent/descent and lying in various positions over an extended period of time (hours or days). Machine learning techniques such as K-nearest neighbour, decision trees, support vector machine, logistic regression and discriminant analysis are often used to classify these common activities of everyday living [132, 137]. Activity classification can provide clinicians with valuable information about the decline in health or independence of elderly living at home, the activity levels of persons living with conditions or diseases, or the detection of falls or accidents [135].

Inertial-based human spatiotemporal and kinematic analysis requires complex sensor fusion and pose estimation methodologies to process raw MARG data. Numerous studies have demonstrated good agreement when comparing spatiotemporal and kinematic measures derived from IMU and MARG based motion capture systems with gold standard 3D OMC systems in clinical, ergonomic and sporting applications [43, 138-142]. Similar to traditional motion capture methods, researchers have suggested the accuracy of IMU and MARG based motion capture to be dependent on the algorithms and methodologies used to process the raw data captured by the device [143, 144].

Researchers conducting previous experimental studies and reviews have primarily focussed on either the overall validity of inertial motion capture (IMC) (excluding methodology considerations) [15, 43, 145, 146], sensor fusion methodologies [147, 148] or position and orientation estimation (pose) methodologies [149-153], making it difficult and time consuming for other researchers and developers to piece together all essential methodological components. Two reviews have attempted to summarise the methodological components of IMC, however these reviews have limited detail around critical considerations such as: sensor fusion, pose estimation and soft tissue artifacts (STA), sensor placement, biomechanical modelling and magnetic calibration, which should be made when developing an IMC solution [41, 42]. The following technical summary is presented with the aim to provide background and reference on all methodological components which must be considered when implementing an IMC solution for a given application (Figure 5.1). Presenting such a summary will reduce the time spent by researchers and developers establishing the fundamental methodological components of IMC prior to further developing current techniques and enhancing the rate of development and utilisation of IMC.

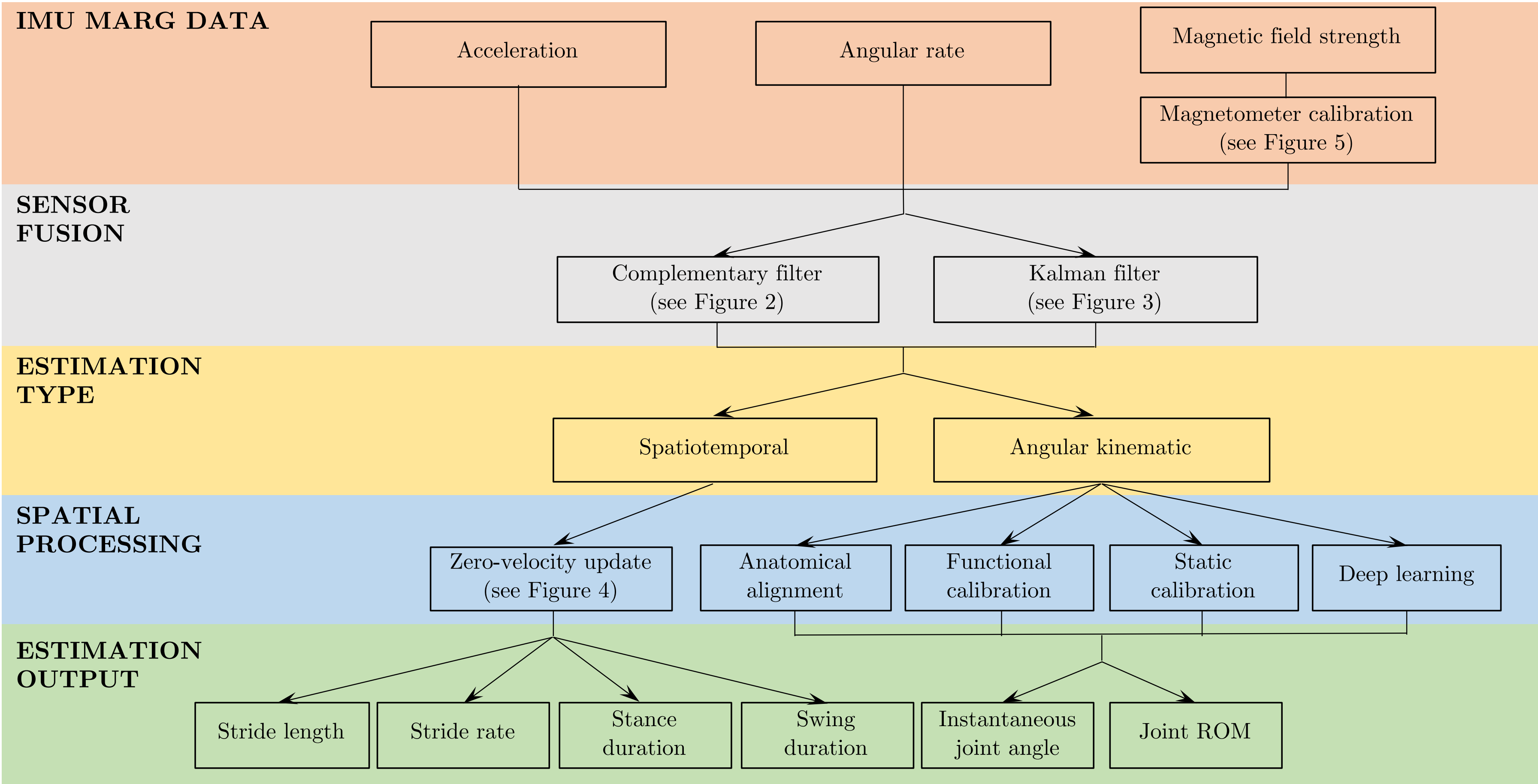


Figure 5.1 Workflow of IMC and where sections of this technical summary lay within the general methodological structure.

## 5.4 SENSOR FUSION

The process of sensor fusion reduces the error inherent in the orientation estimation obtained from raw MARG data. The output of the sensor fusion step is used in subsequent steps of data processing toward the estimation of kinematic and spatiotemporal measures using IMC.

Inertial measurement units consist of an accelerometer and gyroscope to measure linear acceleration and angular rate, respectively. In addition to accelerometers and gyroscopes, MARG sensors include a magnetometer to measure magnetic field strength [154].

Integration of the angular velocity measured by the gyroscope provides an orientation estimation of the sensor at each time point relative to its initial orientation in the local frame. Integration of the gyroscope bias, which is inherent in the sensor at manufacture, leads to a slowly drifting (low frequency) cumulative error in the orientation estimation [148]. As the orientation is estimated in the local sensor frame, additional processing is required to establish a global reference frame, where a relationship between the orientation of each device in the network can be established [148]. This simplistic approach of integrating angular rate measures for device and body orientation is insufficient for reliable human motion capture.

Accelerometers measure acceleration caused by gravity as well as acceleration caused by the motion of a body to which the sensor is attached. The measurement of acceleration due to gravity enables an estimation of the 'up' direction (pitch and roll) of the sensor in the global reference frame [148]. The pitch and roll orientation estimation of the accelerometer may therefore be used to correct the pitch and roll component of the drift caused by the integration of the angular rate signal. Acceleration measurements are however corrupted by high frequency noise caused by movement of the sensor, leading to error in the pitch and roll orientation estimation when the sensor is in a non-quasi-static state [148].

Magnetometers measure the magnetic field strength of the Earth, enabling the definition of the Earth's horizontal North/East plane (heading or yaw) [148]. Similar to both the gyroscope and accelerometer, the magnetometer has its own inherent error in the orientation estimation. Ferromagnetic disturbances in the surrounding environment, causing the signal to be corrupt by high frequency noise, result in error in the orientation estimation by the magnetometer [154, 155].

Sensor fusion algorithms can be used to take advantage of the orientation estimation obtained by the gyroscope, and the global references obtained by the accelerometer (pitch and roll) and magnetometer (yaw), whilst reducing the errors caused by the high and low frequency noise associated with each of the measures. The two most common methods of sensor fusion are the complementary filter [154, 156, 157] and the Kalman filter [158-160].

### 5.4.1 COMPLEMENTARY FILTER

A complementary filter is used to combine two measurements of a given signal, one consisting of a high frequency disturbance noise, and the other consisting of a low frequency disturbance noise, producing a single signal output measurement [148]. Using filter coefficients/gains, the reliance on each input and response time for drift error correction can be manipulated, with shorter response times coming at the expense of greater output noise [148].

When applied to MARG data for orientation estimation, one such approach is to use a two-stage complementary filter to obtain a combined orientation estimation with a smaller error component than what could be obtained by using just a single sensor signal [161]. The application of a two-stage complementary filter can be briefly described as follows (see also Figure 5.2), with detailed derivation of complementary filter equations presented in Valenti, et al. [161].

- Orientation is estimated using accelerometer data.
- Accelerometer orientation estimation is corrected based on a defined threshold adhering to the deviation from a known quantity (e.g., gravity). Correction is achieved using a gain to characterise the cut-off frequency of an applied filter.
- The corrected accelerometer-based orientation estimation is fused with the low-frequency corrupt gyroscope-based orientation estimation, producing a complementary estimation of the device pitch and roll.

- Magnetometer measures are examined for environmental ferromagnetic disturbances and orientation estimation from the magnetometer data is corrected using a similar approach to the accelerometer-based orientation correction.

- The pitch and roll (gravitational) orientation estimation is fused with the magnetometer yaw orientation estimation to provide a full attitude and heading orientation estimation.

Although the accuracy of the orientation estimation and computational expense of the process can differ slightly between various complementary filter methodologies [154, 157], the complementary filter is generally computationally less expensive than other sensor fusion approaches [159, 162]. The low computational cost of the complementary filter enables the use of low power, wearable MARG devices, where data processing can be undertaken onboard the MARG device and streamed live for visualisation on external devices [154]. The smaller size of such wearable MARG devices may be particularly important for human motion capture where minimal disturbance to a person's natural movement is desired, enhancing the ecological validity of the analysis. The computational efficiency of the complementary filter however generally comes at the cost of the ability to tune the filter for a given application or environment, often resulting in an overall greater error in orientation estimation with reference to ground truth, when compared to sensor fusion approaches such as the Kalman filter [147, 159].

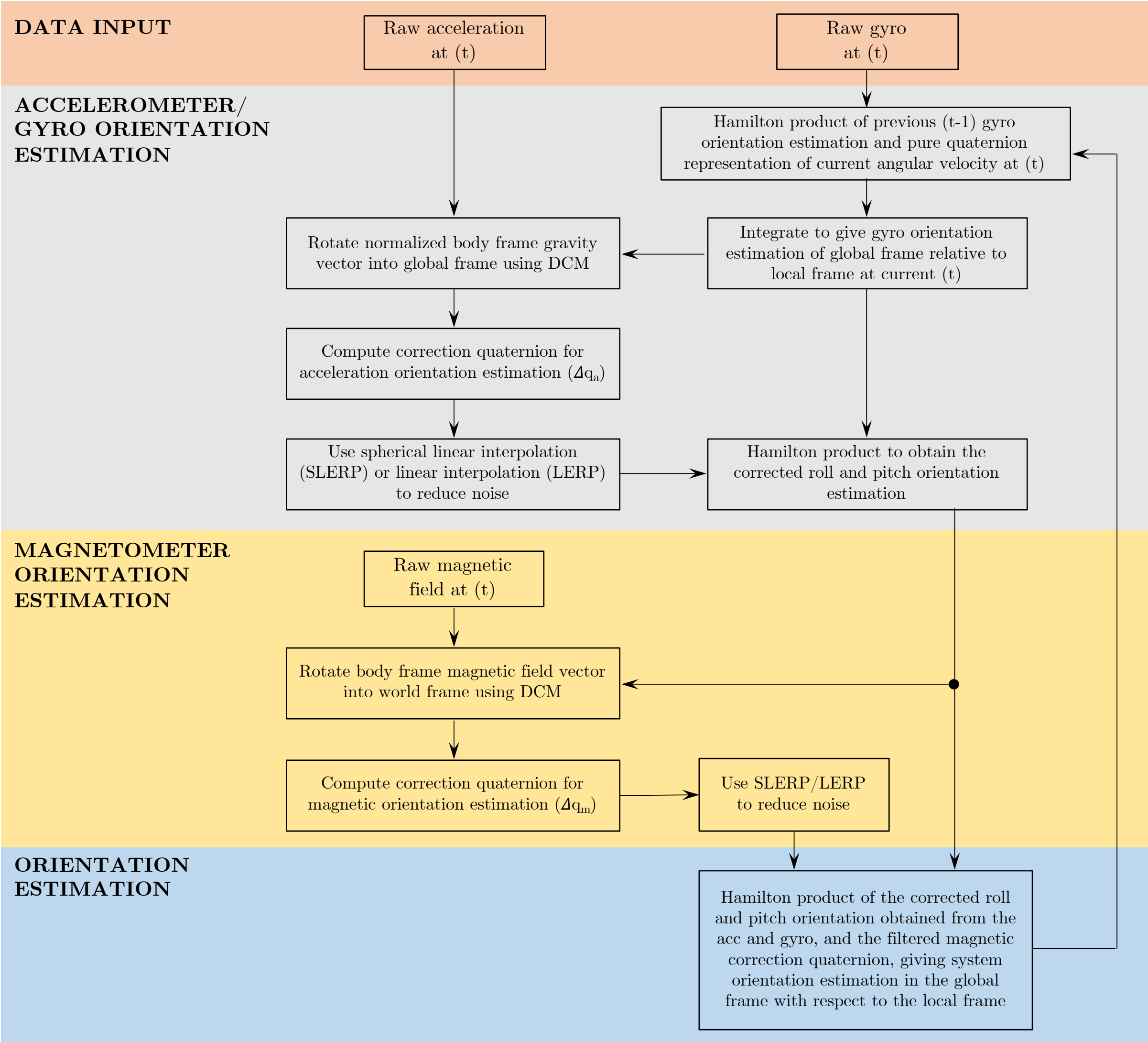


Figure 5.2 Complementary filter approach example (based on Wu, et al. [163] and Valenti, et al. [161]). © [2015] IEEE.

### 5.4.2 KALMAN FILTER

The Kalman filter works on a prediction and correction process to estimate the state of a dynamic system from noisy measurements [162]. Various forms of the Kalman filter have been used for orientation estimation, with varying levels of complexity and assumptions being used in each solution [159, 164-166].

In its most simplistic form and using MARG data, five steps are typically employed in a Kalman filter-based solution for each time interval [165].

- The a priori state estimate is obtained from the accelerometer, gyroscope and magnetometer output measures.

- The a priori error covariance matrix is established in an attempt to compensate for sensor bias and Gaussian measurement noise.

- As the measurement model of the accelerometer and magnetometer is inherently non-linear, a first order Taylor Maclaurin expansion of the current state estimate is performed by computing the Jacobian matrix.

- Using the a priori state estimate, the a priori error covariance matrix and a set of measurement validation tests, an expression for the Kalman gain is established. The Kalman gain is used to give relative weight to either the current state estimate or the measurement.

- An updated estimate (a posteriori) of the state estimate and error covariance matrix can then be computed.

While these steps are generalisable to most Kalman filters, Figure 5.3 depicts, specifically, a block diagram of an indirect Kalman filter applied to MARG data [167, 168]. For brevity, state models and Kalman equations have been excluded from this paper, as such, the reader is directed to MEMS Industry Group [167] and The MathWorks Inc. [168] for further derivation of the particular case presented.

Although the Kalman filter is recognised for its greater tunability for a given application or environment, and thus reduced error in orientation estimation when compared to the complementary filter approach [147], the Kalman filter process is complex and requires high grade IMU and/or MARG sensors. The combination of high sampling rates (up to 30 kHz) required for the linear regression iterations, large state vectors and additional linearisation through an extended Kalman filter make the Kalman filter based solution computationally expensive [154]. Where onboard processing is required for live visualisation of human motion, the physical size of the equipment required to satisfy these high computational demands may currently inhibit natural movement of the person wearing the device [154].

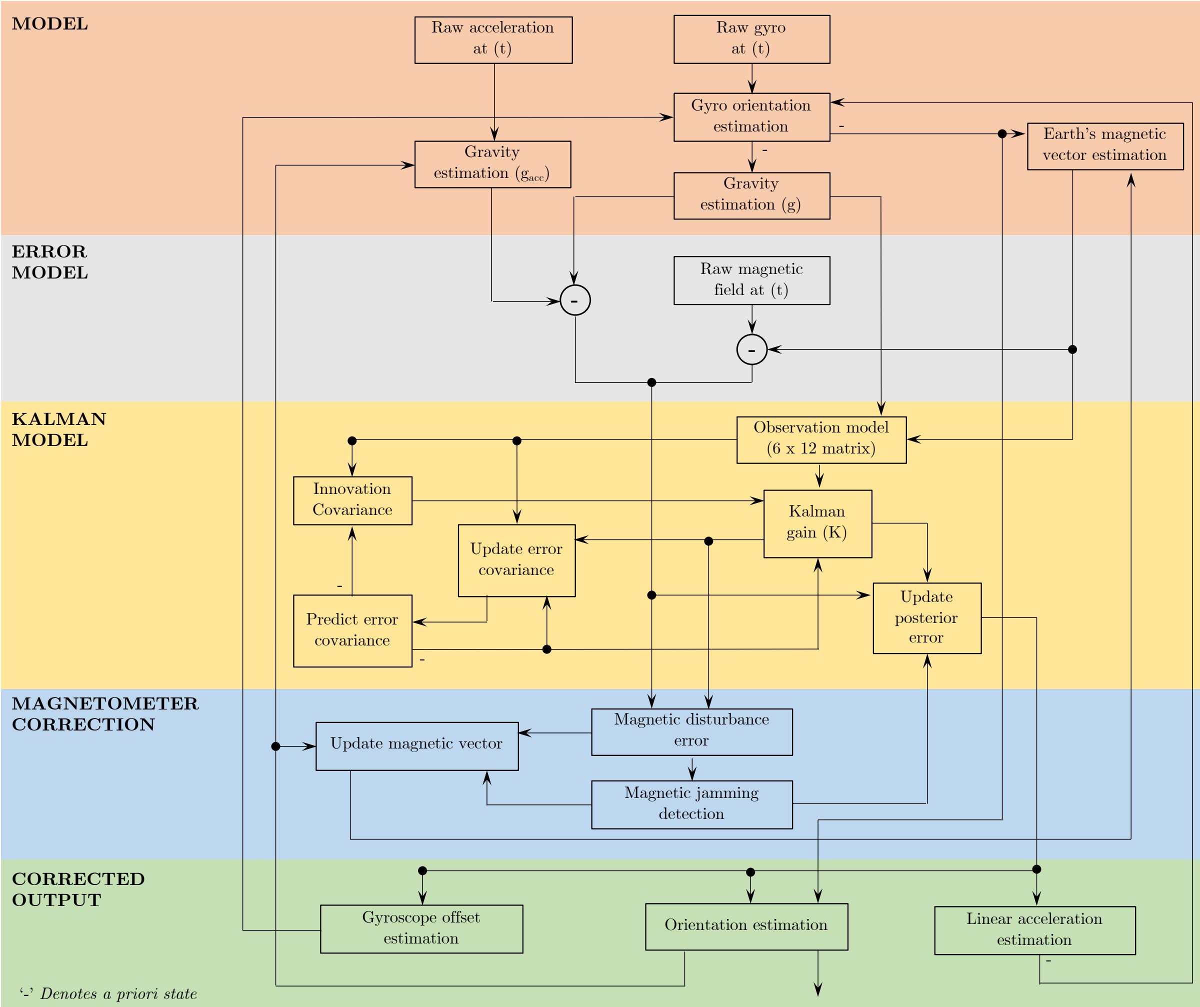


Figure 5.3 Kalman filter approach example (adapted from MEMS Industry Group [167] and The MathWorks Inc. [168]).

## 5.5 POSE ESTIMATION

Orientation estimations of each IMU/MARG device obtained by means of sensor fusion, must be further processed to obtain spatiotemporal and angular kinematic estimations of the human body. To estimate spatiotemporal and angular kinematic measures of the body, the position and orientation (pose) of the body/body segment must be established. Where both raw MARG data and sensor orientation estimation data (obtained as a result of sensor fusion) are typically used in this process, some of the processing methodologies used for angular kinematic estimations may also be required when establishing spatiotemporal estimations (namely sensor to segment alignment).

### 5.5.1 ANGULAR KINEMATICS

The placement of an IMU or MARG device on the segment immediately proximal and distal to a joint and taking the relative orientation of the two segments, has been commonly proposed as a possible method of estimating joint angular kinematics [169]. The challenges associated with the estimation of joint angular kinematics using this method arise from the complexity of accurately estimating the device orientation using sensor fusion methods (as described previously), and the alignment of the sensor coordinate system to the corresponding segment coordinate system [85]. This process is commonly referred to as sensor to segment alignment. The three primary methods of sensor to segment alignment used in previous literature are the: anatomical alignment; functional calibration; and static calibration methods. Most recently, deep learning techniques have also been used for sensor to segment alignment.

#### 5.5.1.1 *ANATOMICAL ALIGNMENT*

The anatomical alignment method sees the alignment of the local rotational axes within the IMU/MARG device, with the anatomical axis of the body segment to which the device is attached [138, 139, 170, 171]. The relative rotation as estimated by the proximal and distal sensor for the aligned axes can then be assumed as the joint angle estimation throughout a movement. The advantage of the anatomical alignment method is seen in the use of the local (device) coordinate system for orientation estimation, thus not requiring any form of mathematical transformation from a local to a global coordinate system. The associated error and resultant overall accuracy of the joint angle estimation when using this method is highly dependent on the proper alignment of each device axes with the axes of the segment of interest [151, 171], and therefore may require the assistance of an experienced anthropometrist or specialised alignment equipment [45].

#### 5.5.1.2 *FUNCTIONAL CALIBRATION*

Alignment of the local (device) coordinate frame with the segment coordinate frame has been achieved through functional calibration (FUNC) methods [172-174]. Functional calibration methods typically use predefined calibration movements and a set of assumptions (limiting the degree of freedom of a joint) to establish the average axis of rotation of a joint. Using the FUNC method, a MARG device may be arbitrarily placed on the limbs proximal and distal to a joint, and the orientation of each device in the global reference frame may be determined by an appropriate sensor fusion algorithm. With the two devices secured to the segments of a participant, the participant is asked to perform an isolated rotation about two single joint axes. For example, the first rotation may be about the longitudinal axis (i.e. internal/external rotation at the hip), while the second rotation may be about the medial/lateral axis (i.e. flexion/extension at the hip) [173]. Using numerical methods, the common axis of rotation can be determined, with the remaining axis of rotation assumed to be perpendicular to the two axes established from the movements [173].

The primary advantage of the FUNC method is in the ability to arbitrarily place sensors on each segment, thus eliminating the requirement of assistance of an experienced anthropometrist for sensor placement or additional alignment devices. Although the FUNC method has been further developed to be implemented with arbitrary movements [169], some clients may be unable to perform the required functional calibration movements [175]. Additionally, the numerical and optimisation methods used to establish a common axis of rotation between segments are typically computationally expensive, resulting in the requirement of devices with greater processing capacity or off-board processing [169, 176, 177].

#### 5.5.1.3 *STATIC CALIBRATION*

The static calibration (STAT) method is a somewhat hybrid approach of the anatomical alignment and FUNC methods. The STAT method requires a single axis of a "base" MARG device (typically located on the pelvis) to be aligned with a single axis (typically medial/lateral) of the segment [149, 178]. The advantage of this method is once one axis of a single sensor has been aligned with a segment axis, all MARG devices attached to other segments can be arbitrarily oriented.

A short, static, neutral calibration pose (five seconds) is captured to orient each sensor in the global frame using an appropriate sensor fusion algorithm. The vertical axis of the base MARG device is then corrected (rotated) to align with the gravity vector, leaving the remaining unknown (anterior/posterior) axis to be defined as being perpendicular to the medial/lateral and vertical axes [178]. This establishes an initial segment coordinate system in the global frame which may be used for all other segments, assuming all other segments were aligned during the calibration pose.

The arbitrarily aligned axes of the MARG devices attached to all other segments are then transformed to the initial segment coordinate system established from the base MARG using a mathematical transformation. Once the initial orientation of each segment in the global frame is known, and thus can be tracked throughout a movement, a joint angle is calculated as the difference in orientation of two segments in the global frame.

As a somewhat hybrid approach, the STAT method provides the advantage of arbitrary device placement (except for the base unit), and relatively short computational times, when compared to FUNC methods. Similar to the anatomical alignment method, the STAT method assumes the accurate alignment of the single axis of the MARG device with a chosen axis of the base segment. As this is only a requirement for a single sensor/segment pair, the time taken by an experienced anthropometrist or trained person in assisting with the placement of sensors may be reduced. Where misalignment of the base sensor and/or misalignment of the participant body segments with a standard anatomical pose during static calibration is encountered, error in the sensor to segment alignment will occur.

#### 5.5.1.4 *STATE-OF-THE-ART DEEP LEARNING*

To the author's knowledge, only one study has used state-of-the-art deep learning approaches for sensor to segment alignment in human motion capture [150]. The methodology used a set of both real and simulation data to train a model to identify the orientation of a MARG device attached to a body segment and to align the axes of the device with the anatomical axes of the corresponding segment. Sensor to segment alignment were performed for the pelvis and bilateral thigh, shank and foot. Three datasets were used to train and test the model, with a final optimal model established using a combination of these datasets.

Dataset one consisted of real inertial data collected from 28 participants walking for six minutes in a figure eight pattern with a single inertial device orientation. Dataset two consisted of a sample of four participants walking back-and-forth in a 5 m line for one minute with nine different inertial device orientations. Dataset three consisted of simulation data established from a publicly available OMC dataset of 42 participants performing different walking styles. Inertial devices were mapped to the underlying model of dataset three using 64 alignment variations [150]. The final optimal model used datasets one, two and three to train the model and a single participant from dataset two and a single participant from dataset three (not included in the training dataset) for testing. A mean alignment error of 15.21° was reported using the final optimal model, with a mean computational time for the training of such model of 48 hours [150].

Based on the results of Zimmermann, et al. [150], deep learning methods appear to require a large set of training data and a large number of alignment variations to ensure reduced error and optimal sensor to segment alignment [150]. Although the development of the method of sensor to segment alignment using deep learning techniques is in its relative infancy, further development of the method may result in sensor to segment alignment using deep learning becoming common practice for IMC.

In addition to joint kinematic measures, researchers are often also interested in recording spatiotemporal measures for full gait analysis. Many of the data processing methods to achieve spatiotemporal measures using IMC build on and rely upon the assumption of sensor to segment alignment.

### 5.5.2 SPATIOTEMPORAL

While gait event detection such as heel strike and toe-off, and subsequent spatiotemporal parameters such as swing and stance duration, and cadence may be identified through various relatively simple threshold approaches using measures of angular rate and linear acceleration [179], estimation of stride length is typically more complex [180, 181]. Two approaches for stride length estimation have primarily been used in previous literature; the biomechanical modelling [182-184] and strap-down integration approach [185].

In the biomechanical modelling approach, the lower limbs are typically modelled by means of a double pendulum [182-184]. Such modelling approach is however, restricted to the analysis of movement in the sagittal plane, limiting the accuracy of the method for stride length estimation of persons with irregular gait patterns [185, 186]. Although not free from its own challenges, the strap-down integration approach enables multi-planar analysis, and as such, will be the focal method for spatiotemporal estimation in this technical summary [185].

Assuming sensor to segment alignment has been implemented on a foot/shoe mounted MARG sensor, double integration of the raw acceleration measures, after the subtraction of acceleration due to gravity, theoretically provides an estimation of the distance travelled throughout a given movement duration. Integration of the high frequency noise within the acceleration measure results in a cubically growing positional error [185]. The strap-down integration approach, by means of zero-velocity update (ZUPT), has been generally accepted as the most robust approach to overcome the propagation of error caused by integration of acceleration data for position estimation [180]. The ZUPT algorithm has seen multiple variations [180, 181, 185, 187, 188] and typically relies on the accurate identification of the stance phase of the gait cycle (where the foot momentarily experiences zero velocity relative to the ground), to "reset" the cubically growing error caused by the double integration of noisy raw linear acceleration data [180, 185, 189, 190].

Thresholding techniques have been used to identify phases of a gait cycle, whereby the resultant angular velocity of the foot is monitored for zero angular rotation about any axis throughout the stance phase [191]. Although the exact value of zero angular rate may not be reliably captured in real life, setting a threshold of, for example, 1 rad/s has been suggested to reliably capture the stance phase during walking [191]. For running or other higher velocity movements where the duration of the stance phase is shorter than walking, the threshold value will likely require adjustment, or the addition of other measurements to the logic statement may be required [181, 192]. The use of both foot angular velocity and orientation data has been demonstrated as a possible method of identifying instances of heel strike and toe off during a gait cycle [179]. Using this method, toe-off may be identified by searching for the first maximum in angular velocity within a specified search window spanning peak ankle plantar flexion. Similarly, heel strike may be identified by searching for the zero angular velocity crossing point within a search window spanning peak ankle dorsiflexion [179]. Search window sizes should be set specific to a given movement (e.g., walking, running, pathological gait pattern), with the most appropriate window sizes typically achieved through an iterative process.

As the sensor orientation is transformed from the sensor frame to the navigation or global frame, the acceleration due to gravity can be removed, leaving just the acceleration due to the motion of the sensor. The remaining motional acceleration can then be integrated to give the estimated velocity of the sensor. Where the stance phase (zero velocity) has previously been identified through the identification of heel strike and toe-off events, the integrated velocity and thus measurement error is "reset" to zero [191]. By resetting the velocity to zero during each stance phase, the drift error is limited to the relatively short duration of a stride. The corrected velocity may then be once again integrated to give position, where stride length is the difference in position between two consecutive stance phases.

The use of Kalman filtering techniques can improve the accuracy of the described naïve ZUPT approach [181]. Instead of resetting the velocity to zero where a stance phase is identified, the Kalman filter uses an error state vector consisting of biases for acceleration, angular rate, attitude, velocity and position to reset velocity and position to an estimated near-zero value [181, 188].

Although the gait event detection and ZUPT methods described in this summary are a general overview of methods used in previous literature, an example of how a selection of these methods may fit together to estimate gait spatiotemporal parameters is provided in Figure 5.4. The reader is directed to Jasiewicz, et al. [179] and Fischer, et al. [181] for further implementation details.

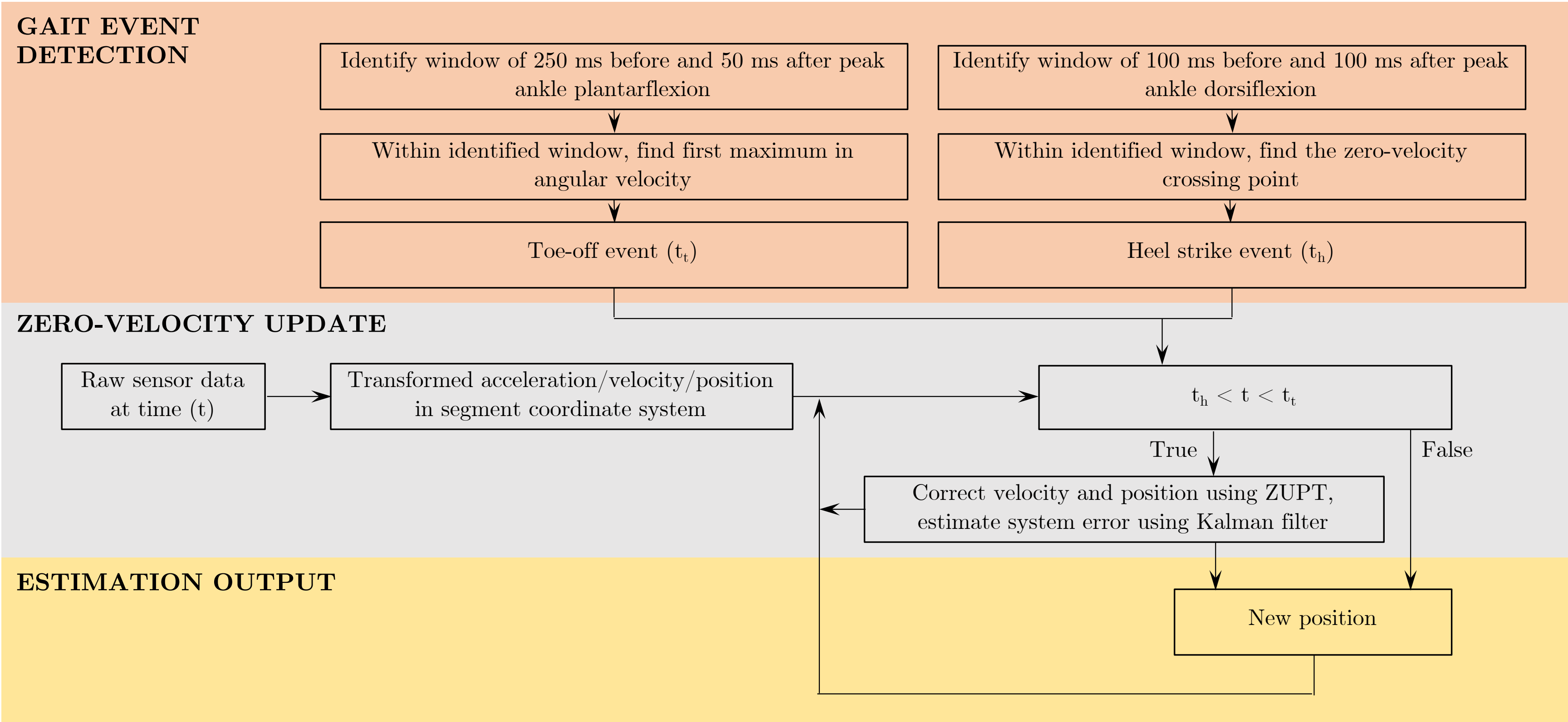


Figure 5.4 Zero-velocity update approach example (based on Jasiewicz, et al. [179] and Fischer, et al. [181]). © [2013] IEEE.

## 5.6 ADDITIONAL CONSIDERATIONS

Aside from selecting the most appropriate sensor fusion and pose estimation processing methodologies for a given application, other components of the methodological design such as device placement, biomechanical modelling methods and magnetometer calibration also warrant consideration to minimise the propagation of errors and optimise the accuracy of an implemented IMC methodology.

### 5.6.1 DEVICE PLACEMENT

Soft tissue artefacts (STA) are suggested to be a significant source of error when measuring human kinematics using OMC methods [193]. Soft tissue artefacts occur when the skin (and underlying adipose tissue and muscle) to which the markers/sensors are attached, move relative to the bone for which the orientation and kinematics of the body is being estimated [193]. Inertial motion capture is also not exempt from the error caused by STA. Where OMC methodologies often use rigid clusters of markers [194] and/or anatomical modelling assumptions [195] to reduce the effects of STA, research into the reduction of STA effects on IMC is limited [196, 197]. Frick et al. presented a two-part study using numerical methods to reduce the effect of STA on inertial-based joint centre estimations. The method used a single frame optimisation (SFO) algorithm to determine the location and orientation of the joint centre relative to the sensor at each time frame. Although the method showed good agreeance with state-of-the-art OMC joint centre estimations on a mechanical rig, the SFO cost function assumes the joint centre to be undergoing negligible acceleration, which may be violated for many applications. The method proposed by Frick, et al. [196] demonstrates the potential in the reduction of STA when using IMC methods, however, further development is required before the SFO method is considered a practical solution for more complex applications [196, 197].

Spatiotemporal parameters such as stride length, stride time and contact time have regularly been obtained from a single IMU/MARG device worn on the pelvis, ankle or foot [124, 125, 198, 199]. The validity of these IMU/MARG derived spatiotemporal measures has been suggested to be affected by the location of the device [200]. When compared to ankle and pelvis worn IMU/MARG devices, foot mounted IMU/MARG devices have been found to result in greater validity of spatiotemporal estimations [198, 199]. Positioning the device closer to the source of impact (ground) may result in less signal attenuation from STA and naturally occurring shock absorption by proximal segments and thus greater accuracy in gait cycle event detection (such as heel strike, mid-stance and toe off) [125, 201].

### 5.6.2 Biomechanical modelling

Often considered a gold standard, OMC typically combine anatomical assumptions and anatomical marker locations to estimate joint angle kinematic measures using modelling techniques (modelled measures) such as the Plug-in Gait model (Oxford Metrics, Oxford, UK). Inertial motion capture typically rely on the un-modelled relative orientations of a proximal and distal sensor to a joint for joint angle estimation [127]. Due to these differences in modelling assumptions, the modelled measures obtained from OMC are expected to differ somewhat from the naïve relative joint angles commonly obtained using IMC [127, 202].

Brice, et al. [127] compared IMC relative joint angles with OMC relative angles (un-modelled with reflective markers attached to the inertial device), and IMC relative joint angles with OMC modelled measures for the pelvis and torso in the sagittal, frontal and transverse plane. Participants performed three sets of a self-selected slow and two sets of self-selected fast rotation of the torso relative to the pelvis in each anatomical reference plane. Good agreement was reported between the IMC relative joint angles and the OMC relative angles (RMSE%: 1 – 7%). Less agreement was reported between the IMC relative joint angles and OMC modelled measures (RMSE%: 4 – 57%). Similar results to Brice, et al. [127] have been found by Cottam, et al. [202] for pelvis, thorax and shoulder joint angles during cricket bowling. No significant differences were reported between IMC and OMC relative angles, however significant differences in shoulder rotation, thorax lateral flexion and thorax to pelvis flexion-extension and lateral flexion were reported between IMC relative joint angles and OMC modelled joint angles at various stages of the cricket bowling delivery stride [202].

The results of Brice, et al. [127] and Cottam, et al. [202] suggest that IMC is capable of accurately measuring pelvis and torso relative angles during slow and fast multi-planar movements, however, these relative angles may not be representative of, or directly comparable to those of an OMC system where anatomical modelling is used to estimate joint angles. It has recently been suggested that the joint kinematics measured using both OMC and IMC methods may not represent the true kinematics of the joint due to the underlying assumptions made when using each method [140, 142, 145]. Further development of OMC and IMC modelling techniques may be required to enable valid comparison between OMC and IMC joint angle estimations, with development of each method being further extended to achieve a greater representation of the true kinematics of the joint.

### 5.6.3 MAGNETOMETER CALIBRATION

Although the inclusion of a magnetometer in an IMC system allows the definition of the orientation of the MARG device in a global North, East Down (NED) reference frame, such global orientation estimation may be corrupted by ferromagnetic disturbances within the environment. Often, the validation of IMC systems occurs within a laboratory environment where gold standard systems (such as OMC systems) are situated and used for comparison. Measurement equipment within a laboratory, as well as structural iron in the flooring, walls and ceiling of the building have proven to be a considerable source of ferromagnetic interference [203]. When using MARG devices for motion capture within such environments, a magnetic calibration of each MARG device is recommended [203].

Magnetic calibration procedures reduce the effect of hard iron effects (fixed bias with respect to the local reference frame of the sensor) and soft iron effects (variable distortion dependant on the orientation of the sensor) [155]. In an undisturbed environment, the magnetic field strength data of a magnetometer rotated through a full range of 3D rotation should form a perfect sphere centred around some origin. Ferromagnetic disturbances distort this ideal spherical formation of data to the extent of an ellipsoid shape (due to soft iron effects) and shift the centre of the ellipsoid away from the origin (due to hard iron effects). To correct for hard and soft iron effects, a best fit ellipsoid is established using parameter solving algorithms in an attempt to form a spherical representation of the raw data (Figure 5.5) [155].

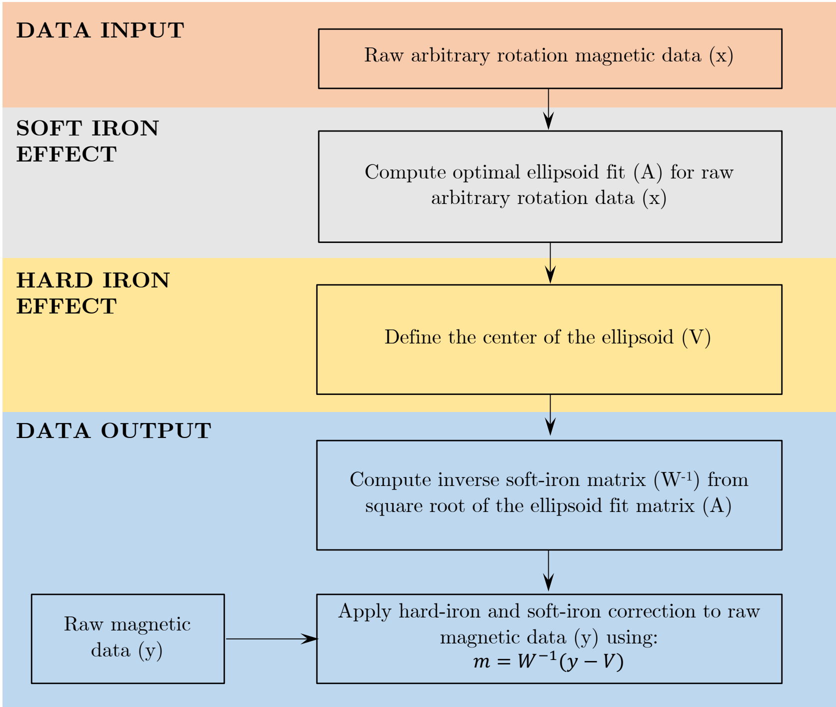


Figure 5.5 Magnetic calibration approach example (based on Ozyagcilar [155]).

Performing movements > 40 cm above ground level, starting data capture in an area of low ferromagnetic disturbance and ensuring sufficient capture time before commencing the movement to allow the sensor fusion Kalman filter to compensate for ferromagnetic disturbances have also been shown to reduce error in orientation estimation caused by ferromagnetic disturbances [203]. At minimum, researchers and developers should attempt to correct for yaw estimation error caused by hard iron effects, and where appropriate implement the aforementioned additional strategies based on the environment in which the IMC system will be used.

### 5.6.4 Error propagation

The error associated with each stage of data processing propagates toward a total IMC system error. For example, the combined error in a single body segment orientation estimation is the sum of the sensor fusion error, the sensor to segment alignment error and any additional error caused by STA or biomechanical modelling assumptions. Where the goal may be to estimate the relative orientation between two segments (joint angle), the error in each body segment orientation estimation is once again combined. Careful implementation, and further development of the data processing and error minimisation strategies presented throughout this technical summary will contribute to the reduction in total system error and resultant overall accuracy of IMC systems.

## 5.7 Conclusions and recommendations

Inertial motion capture address many of the limitations associated with traditional motion capture systems including marker occlusion and dropout, expensive equipment costs and the ecological validity of performing movements in a confined laboratory environment. The accuracy of IMC systems are suggested to be primarily dependent on the data fusion algorithms and pose estimation methodologies used to interpret human motion from raw MARG data. Additionally, the effect of STA, device placement, biomechanical modelling methods and ferromagnetic interference within the environment should be carefully considered to enhance the accuracy and validity of MARG derived spatiotemporal and kinematic estimations.

# CHAPTER 6:

# METHODOLOGICAL VALIDATION STUDY

# 6. Validation of spatiotemporal and kinematic measures in functional exercises using a minimal modeling inertial sensor methodology

## 6.1 Preface

Chapter 6 assesses the validity of a proposed inertial motion capture (IMC) methodology developed using the most appropriate IMC data processing methodologies outlined in Chapter 5. The IMC methodology was found to be suitable for the biomechanical analysis of functional fitness exercises (whilst being transferrable to strongman exercises), and practically reproducible by researchers with an intermediate Matlab skillset. Question 3 *"How may current inertial motion capture methods be used and further developed to characterise the biomechanics of athletes performing strongman exercises?"* was addressed in this chapter.

Supplementary tables referenced throughout this chapter can be found in Appendix 4.

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## 6.2 Abstract

In this study, a minimal modelling magnetic, angular rate and gravity (MARG) methodology is proposed for the assessment of spatiotemporal and kinematic measures during functional fitness exercises. Thirteen healthy persons performed repetitions of the squat, box squat, sandbag pickup, shuffle-walk, and bear crawl. Sagittal plane hip, knee, and ankle range of motion (ROM) and stride length, stride time, and stance time measures were compared for the MARG method and an optical motion capture (OMC) system. The root mean square error (RMSE), mean absolute percentage error (MAPE), and Bland–Altman plots and limits of agreement were used to assess agreement between methods. Hip and knee ROM showed good to excellent agreement with the OMC system during the squat, box squat, and sandbag pickup (RMSE: 4.4 – 9.8°), while ankle ROM agreement ranged from good to unacceptable (RMSE: 2.7 – 7.2°). Unacceptable hip and knee ROM agreement was observed for the shuffle-walk and bear crawl (RMSE: 3.3 – 8.6°). The stride length, stride time, and stance time showed good to excellent agreement between methods (MAPE: 3.2 ± 2.8 – 8.2 ± 7.9%). Although the proposed MARG-based method is a valid means of assessing spatiotemporal and kinematic measures during various exercises, further development is required to assess the joint kinematics of small ROM, high velocity movements.

## 6.3 INTRODUCTION

Motion capture is a fundamental component of many modern biomechanical analyses. Common technologies used for human motion capture include optical, image/video processing and electromagnetic-based systems [15]. Although considered the gold standard of motion capture, optical motion capture (OMC) systems are expensive, typically limited to a laboratory environment, and suffer from marker occlusion, often resulting in loss of data [204]. Image/video processing systems suffer from similar marker occlusion problems, as well as parallax and perspective error [26]. Electromagnetic systems are limited to slow movements due to a low sampling frequency and are susceptible to large errors where ferromagnetic disturbances are present in the environment [15]. The limitations of current motion capture technology, particularly for field-based research, have prompted researchers to explore alternate technology for human motion capture.

Advancements in inertial measurement unit (IMU) and magnetic, angular rate and gravity (MARG) technologies has seen the development of affordable, compact, and powerful devices [158]. Inertial measurement units measure the tri-axial angular rate and linear acceleration, while MARG devices also measure the tri-axial magnetic field strength. By attaching IMU/MARG devices to individual body segments and performing specialised processing of the output data, the position and orientation of each segment and the resultant kinematics of the body can be estimated [205]. High sampling rates, an affordable equipment cost, and the ability to stream data live or collect data directly on the device for future download make IMU/MARG technology an attractive alternative to traditional motion capture systems. Researchers have used both proprietary and researcher-developed IMU/MARG systems to measure human movement for a range of applications, including sporting [43-45, 47, 206, 207], clinical [149, 208-210], and ergonomic [100, 211-213] applications. Literature investigating the validity of IMU/MARG motion capture for the assessment of human kinematics suggests that the accuracy of IMU/MARG motion capture is dependent on the task complexity, movement speed, sensor placement, specific kinematic parameter being analysed, and processing methodology used [145, 153]. Processing methods described in previous validation studies of researcher-developed systems, particularly in the areas of sensor fusion and sensor to segment alignment, provide valuable information for the development of IMU/MARG motion capture technology.

In its most simplistic form, integration of the angular rate data of an IMU/MARG device provides an orientation estimation of the device with respect to its original orientation in a local coordinate frame [147]. Integration of the inherent bias within the angular rate data results in cumulative drift error over time [148]. The acceleration due to gravity measured by the accelerometer may be used to assist in correcting the attitude (inclination) component of this drift; however, the signal becomes corrupt when the device is in a non-quasi-static state [147]. Similarly, the magnetometer data provides a heading (horizontal direction) orientation and can be used to assist in correcting the heading component of the drift. However, this heading estimation is often corrupted by magnetic disturbances within the environment [148].

Sensor fusion leverages the most reliable components of accelerometer, gyroscope, and magnetometer orientation observations at each time point to provide an orientation estimation of the device in a local or global reference frame [41]. While proprietary systems use their own sensor fusion algorithms, the most common methods of sensor fusion incorporate versions of the complementary filter [154, 157, 208] and Kalman filter [160]. Previous literature suggests minimal differences in the orientation estimation accuracy between such sensor fusion methods [147, 214, 215]. The ability to further tune the Kalman filter using various noise and disturbance parameters is suggested to give Kalman filter-based approaches a slight accuracy advantage over complementary filter approaches, albeit at the expense of the computational load [147].

Once the orientation of the IMU/MARG device has been established, the coordinate system of the device must be aligned with the coordinate system of the segment to which it is attached. This process is known as sensor to segment alignment. Sensor to segment alignment methods described in previous validation studies of researcher-developed systems can be categorised as manual alignment with or without the use of specialised alignment devices [45, 138]; static pose estimation [149, 178]; functional calibration [152, 172, 175, 216]; and most recently, deep learning [150]. Although the former three alignment methods have been shown to have a minimal effect on the overall agreement between OMC and IMU/MARG measures [151], the practicality of such sensor to segment alignment methods should be considered.

The manual alignment method (also commonly referred to as the technical anatomical alignment method) requires the precise alignment of the local coordinate system of the

IMU/MARG device with the anatomical coordinate system of each segment. The manual alignment method is the least computationally expensive method [151]; however, it comes at the cost of requiring additional specialised calibration equipment or highly skilled persons to identify anatomical landmarks and place sensors according to these landmarks [45, 138].

Static pose calibration methods remove some of the reliance on the precise alignment of each IMU/MARG device coordinate system with the respective segment coordinate system by allowing the arbitrary placement of all but one device [149, 178]. Mathematical transformations are used to transform a known local sensor coordinate system into a known segment coordinate system via a global coordinate system. This method appears to be a common compromise between computationally simplistic manual alignment and more computationally expensive approaches.

Functional calibration techniques require the client to perform specific movements with the IMU/MARG devices arbitrarily positioned on each segment [152, 172, 175, 216]. Numerical methods are then used to determine the segment or joint coordinate systems from the data collected during the calibration movements. While the functional calibration method allows the arbitrary positioning of all IMU/MARG devices, the computational cost in establishing segment/joint coordinate systems is generally greater than the manual alignment and static pose method [151]. Additionally, certain conditions may prevent some clients from performing the calibration movements [175].

Most recently, deep learning has been used to achieve sensor to segment alignment [150]. This state-of-the-art approach relies on a quantity of previously collected real or simulation motion data to train a model to identify the orientation of an arbitrarily positioned sensor and automatically align it with the segment coordinate system. Although this method is relatively new and has seen limited development, initial research suggests that the method may be computationally expensive and that it requires large sets of existing data for accurate model training [150].

As there is currently no standardised methodology for IMU/MARG motion capture for all applications, it is necessary to learn from the previous literature and validate any novel or application-specific IMU/MARG motion capture methodology. To the best of the authors' knowledge, no previous literature has validated the use of MARG-based motion capture during functional fitness exercises [142, 145], where highly dynamic movements result in large ranges of motion across multiple joints [217].

The aim of conducting this study was to assess the validity of a minimal modelling MARG motion capture methodology (from here on referred to as the MARG method) for the estimation of spatiotemporal (stride length, stride time, and stance time) and kinematic (sagittal plane hip, knee, and ankle joint range of motion (ROM)) parameters when compared to those obtained using an OMC system during various functional fitness exercises. The MARG method uses a minimal modelling approach, which includes the alignment of the sensor to the segment, processing, and anatomical modelling assumptions.

## 6.4 MATERIALS AND METHODS

### 6.4.1 PARTICIPANTS

Thirteen participants, including 10 males (27.6 ± 10.8 y, 82.6 ± 13.5 kg, 181.4 ± 6.2 cm) and three females (31.1 ± 9.6 y, 61.2 ± 5.0 kg, 162.4 ± 5.1 cm), with a broad range of anthropometric characteristics, were recruited for this study to account for body type differences within the fitness population. All participants were required to have undertaken some form of resistance or cardiovascular training of a minimum of twice per week for at least six months prior to testing and be free from any injury at the time of testing. Participants meeting the defined criteria provided written informed consent prior to commencing testing. The study was conducted in accordance with the Declaration of Helsinki and ethical approval was granted for all procedures used throughout the study by the Bond University Human Research Ethics Committee (BH00070).

### 6.4.2 EXPERIMENTAL PROTOCOL

Analysed movements were selected based on their transferability to a range of exercise-related movement patterns [79, 217] and their ability to be performed in a laboratory environment (Figure 6.1). The following subsections provide a description of these five movements.

#### 6.4.2.1 *SQUAT*

Each participant performed three sets of five squat repetitions. Participants were instructed to cross their arms over their chest and perform the squats to a maximum comfortable depth at a self-selected cadence.

#### 6.4.2.2 *BOX SQUAT*

Each participant performed three sets of five box squat repetitions. Participants were instructed to cross their arms over their chest and perform the squats to the depth of a wooden box with the following dimensions: height: 500 × depth: 300 × width: 400 mm.

#### 6.4.2.3 *SANDBAG PICKUP*

Each participant performed three sets of three sandbag pickup repetitions (sandbag mass: 10 kg; diameter: ~400 mm; length: ~400 mm). Participants were instructed to adopt a hybrid stoop and squat lifting technique whereby the participant would initialise the lift with relatively straight legs and a curved upper spine, before positioning the sandbag in their lap and standing using a technique similar to the stone lift from the sport of strongman.

#### 6.4.2.4 *Shuffle walk*

Each participant performed three sets of four to six strides of a modified gait pattern across the test volume, simulating the technique they may use if they were carrying a heavy object. Participants were instructed to vary their stride rate, stride length, and stride width throughout and between sets.

#### 6.4.2.5 *Bear crawl*

Each participant performed three sets of bear crawls across the test volume. Participants were instructed to assume a four-point stance position before performing two to three strides across the test volume.

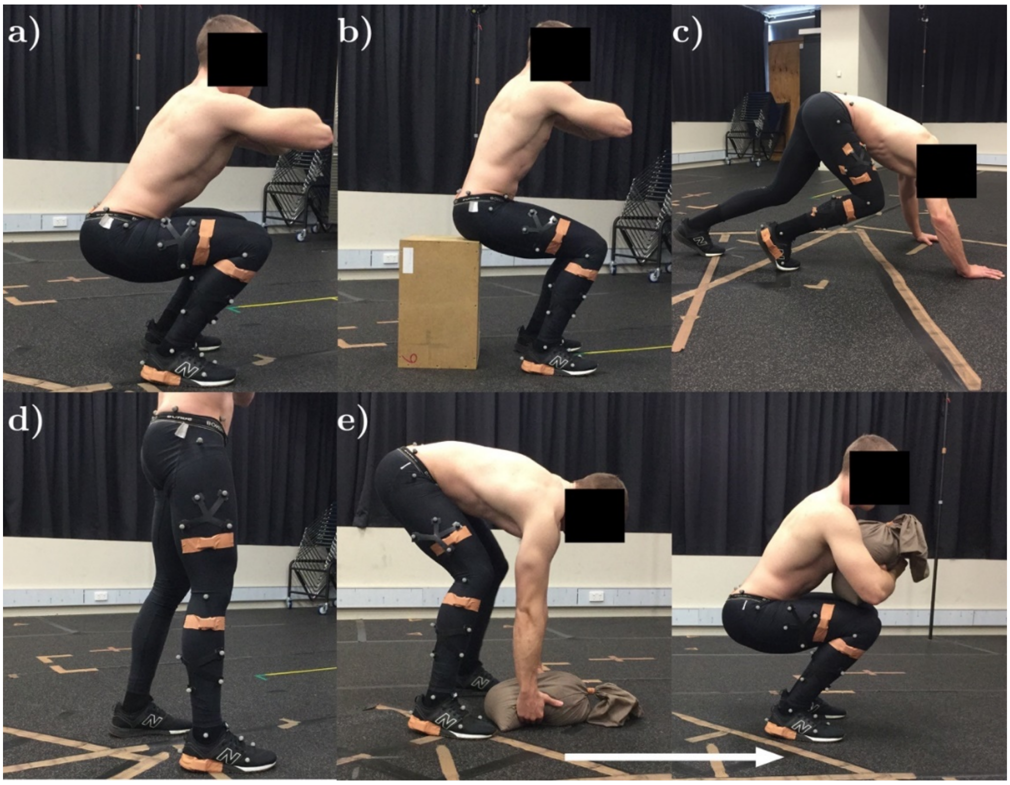


Figure 6.1 Functional fitness exercises: a) squat; b) box squat; c) bear crawl; d) shuffle walk; and e) sandbag pickup. Images reproduced with permission from respective copyright owner and person performing movement.

### 6.4.3 OMC marker placement and processing

A six-camera Bonita Vicon 3D OMC system (Vicon Motion Systems Ltd., Oxford, UK), sampling at 100 Hz, was used as the reference for joint ROM and spatiotemporal estimations [121]. The capture volume was approximately 3 m × 2 m × 2 m. Fifteen 14 mm reflective markers were attached to the landmarks reported in Figure 6.2. Clusters of four reflective markers were attached to the lateral shank and thigh of the participant. Joint angles were estimated via inverse kinematics using Visual3D software (Visual3D, C-motion, Inc.; Rockville, MD, USA) [218].

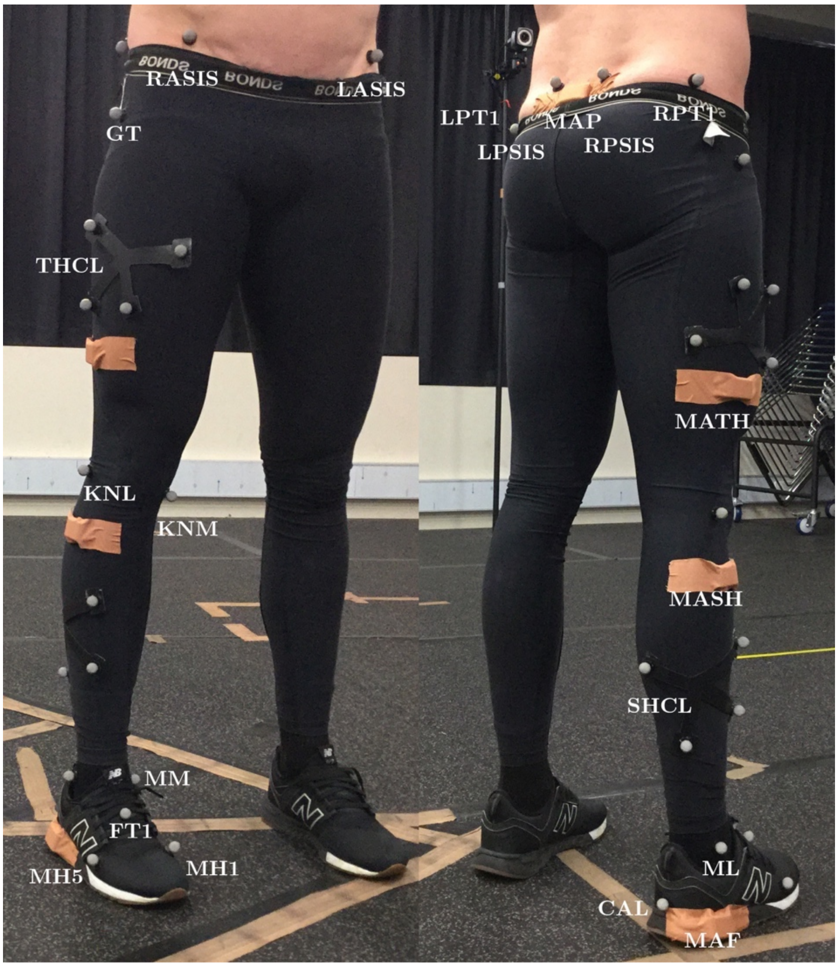


Figure 6.2 Optical motion capture (OMC) and magnetic, angular rate and gravity (MARG) sensor placement: CAL) calcaneus; FT1) foot tracking marker one; GT) greater trochanter; KNL) knee lateral; KNM) knee medial; LASIS) left anterior superior iliac spine; LPSIS) left posterior superior iliac spine; LPT1) left pelvis tracking marker one; MAF) foot MARG sensor; MAP) pelvis MARG sensor; MASH) shank MARG sensor; MATH) thigh MARG sensor; MH1) first metatarsal head; MH5) fifth metatarsal head; ML) lateral malleolus; MM) medial malleolus; RASIS) right anterior superior iliac spine; RPSIS) right posterior superior iliac spine; RPT1) right pelvis tracking marker one; SHCL) shank cluster; THCL) thigh cluster. Image reproduced with permission from respective copyright owner and person pictured.

### 6.4.4 MARG placement and processing

Four MARG sensors (ImeasureU, Vicon Motion Systems Ltd., Oxford, UK) were fixed on a single side of the participant's body (Figure 6.2 and Table 6.1). The location of each MARG sensor was selected for repetitive identification by untrained persons in the field and to minimise the effect of soft tissue artefacts [193]. Each sensor consisted of a triaxial accelerometer (±16 g), triaxial gyroscope (±2000 °/s), and triaxial magnetometer (±4900 μT) with an on-board sampling rate of 1125 Hz (accelerometer and gyroscope) and 112.5 Hz (magnetometer). The Capture.U app (software version 1.1.843, Vicon Motion Systems Ltd., Oxford, UK), installed on an iPad Air 2 (iOS 13.3.1, Apple Inc., CA, USA), was used to initialise and synchronise MARG device data recording. Raw MARG data were processed using distinct methods for kinematic and spatiotemporal measures.

Table 6.1 MARG device positioning.

| Segment | MARG Position |
|---|---|
| Pelvis | Midway between the right and left posterior superior iliac spine. |
| Thigh | Approximately 150 mm proximal to the lateral epicondyle of the femur. |
| Shank | Approximately 100 mm distal to the lateral tibial condyle. |
| Foot | Halfway between the lateral malleoli and the base of the foot. |

### 6.4.5 Kinematic measures

A modified method for determining joint angle kinematics based on Beravs, et al. [178] was developed using a custom Matlab script (The Mathworks Inc., Natick, MA, USA) (Figure 6.3). The following pre-processing and sensor to segment alignment methods were used.

*MARG data pre-processing.* Two different methods for preparing the raw MARG data were used in order to determine the most appropriate method for the selected movement patterns. These will be referred to as the default (DEF) method and the tuned and filtered (TAF) method (Figure 6.4).

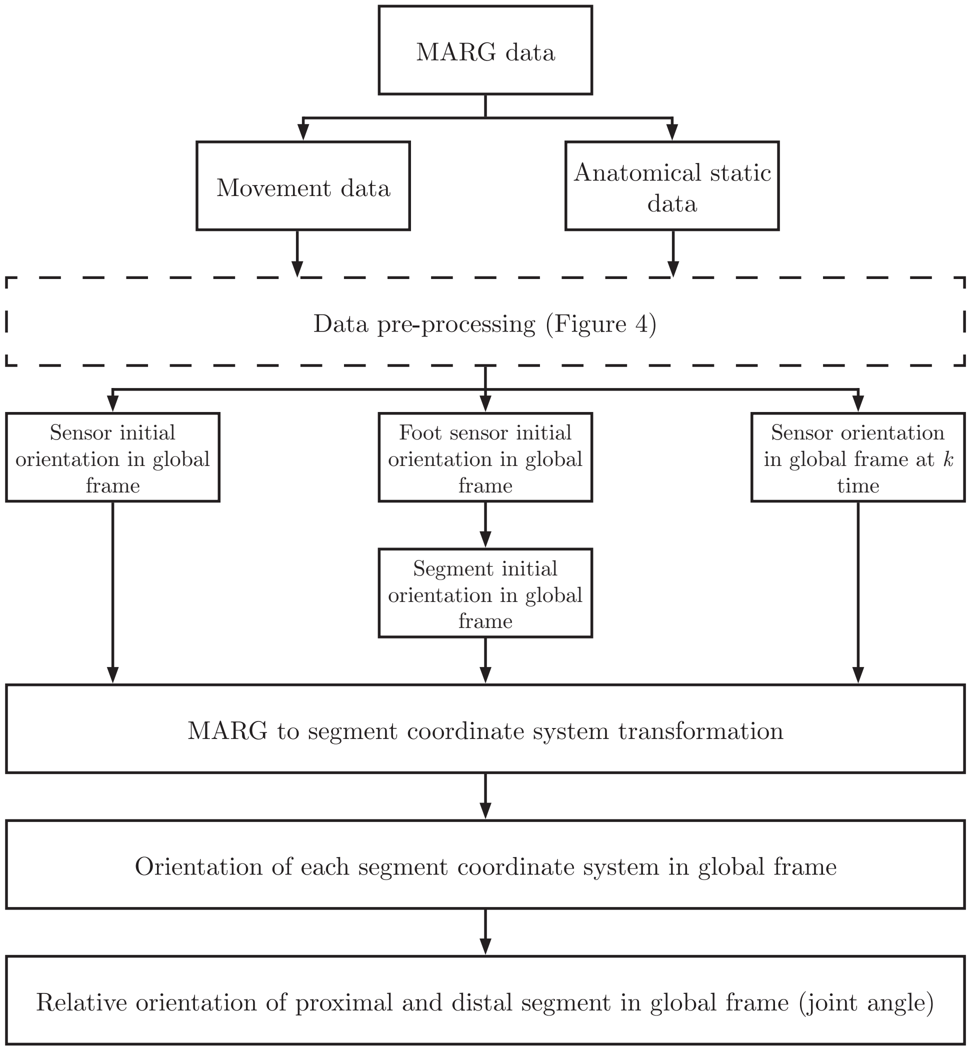


Figure 6.3 Joint angle estimation methodology overview.

For both the DEF and TAF method, the effects of soft and hard iron magnetic disturbances on the raw magnetic field data were reduced by performing a calibration procedure [155]. For the TAF method, gyroscope data were passed through a sixth-order low-pass Butterworth filter with a cut-off frequency of 60 Hz. Filter parameters were established from a frequency analysis of data collected in pilot testing. Acceleration data remained unfiltered in both DEF and TAF methods, based on pilot testing results.

Acceleration, angular rate data (raw for DEF, filtered for TAF), and magnetic field data (calibrated for hard and soft iron effects) were passed into an attitude heading reference system (AHRS) fusion filter to estimate the orientation of each MARG device in the global reference frame (Sensor Fusion and Tracking Toolbox Release 2019a, The Mathworks Inc., Natick, MA, USA). The AHRS filter used a 9-axis indirect Kalman filter to model the error process of the system. The filter allowed initial device and tuning properties to be set for a given movement and environment.

In the TAF method, device tuning properties and biases were established using a combination of a static dataset collected over a four-hour period, information from the device datasheet, and pilot testing data of each exercise. These properties included the following: variance of accelerometer ($(m/s^2)^2$) and gyroscope ($(rad/s)^2$) noise; variance of magnetometer disturbance noise ($\mu T^2$); gyroscope offset drift ($(rad/s)^2$); a compensation factor for linear acceleration drift [0,1]; and the expected magnetic field strength due to the geographic location (Table 6.2). In the DEF method, all filter properties remained as the default properties set by Matlab and the Kalman filter were left to correct for these errors (see MEMS Industry Group [167] for further details).

From the AHRS filter, a quaternion representation of each device in the global frame was established. Quaternion and direction cosine matrix (DCM) representations were used throughout processing to avoid singularities (gimbal lock) inherent when using a common Euler representation [154].

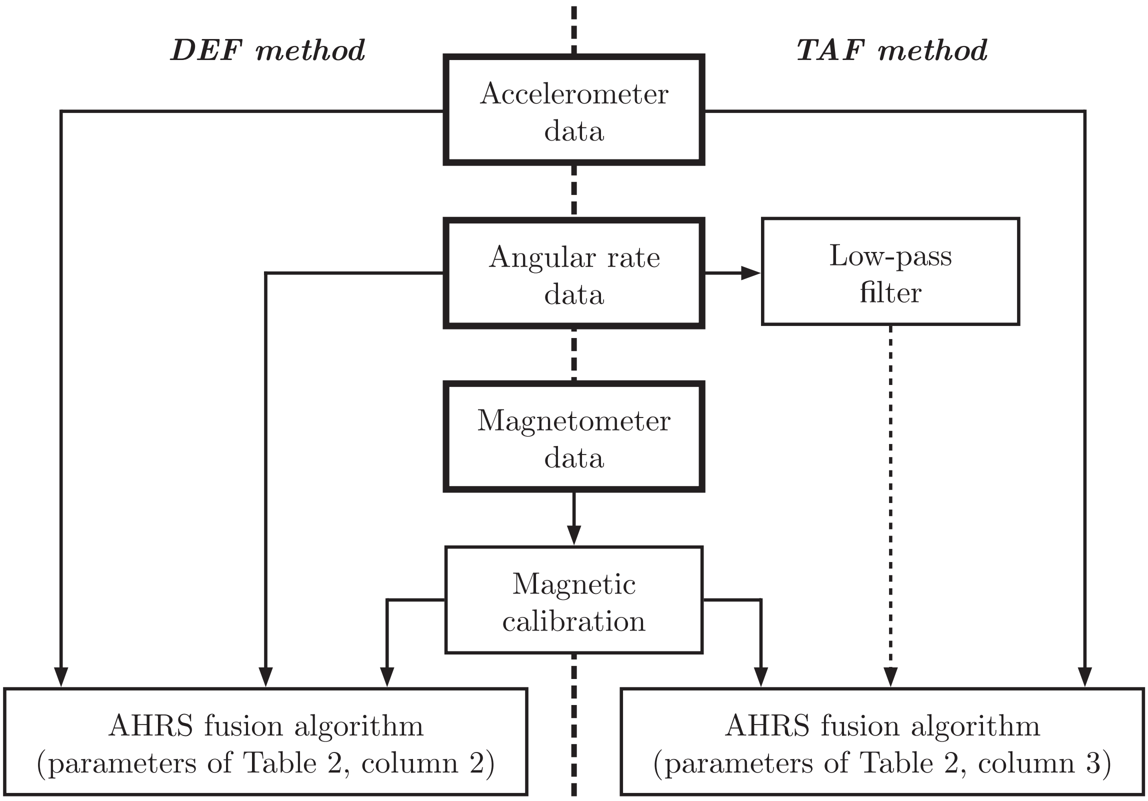


Figure 6.4 Data pre-processing default (DEF) and tuned and filtered (TAF) methods.

Table 6.2 MARG tuning properties.

| Tuning Property | DEF Method | TAF Method |
|---|---|---|
| Variance of accelerometer noise $(m/s^2)^2$ | 1.92 × 10−3 | 3.45 × 10−4 |
| Variance of gyroscope noise $(rad/s)^2$ | 9.14 × 10−4 | 1.40 × 10−6 |
| Gyroscope offset drift $(rad/s)^2$ | 3.05 × 10−13 | 1.77 × 10−8 |
| Magnetometer disturbance noise ($\mu T^2$) | 5.00 × 10−1 | 1.00 × 10−1 |
| Linear acceleration compensation factor | 5.00 × 10−1 | 9.00 × 10−1 |
| Expected magnetic field strength (μT) | 50.0 | (unique to each magnetic calibration) |

The orientation of the MARG sensor positioned on the foot was such that the *x*-axis of the MARG sensor pointed in the anterior/posterior direction of the segment ${}^{GF}q_{MARGfo}$. The cross product of the known foot segment anterior/posterior facing *x*-axis component of the DCM, and the vertical *z*-axis component of the DCM [0,0,1], allowed the *y*-axis component perpendicular to the two known axes to be found. From the orientation of the foot segment in the global frame, the orientation of all segments in the global frame could be assumed to be aligned as ${}^{GF}q_{seg.o}$ and defined as per Figure 6.5.

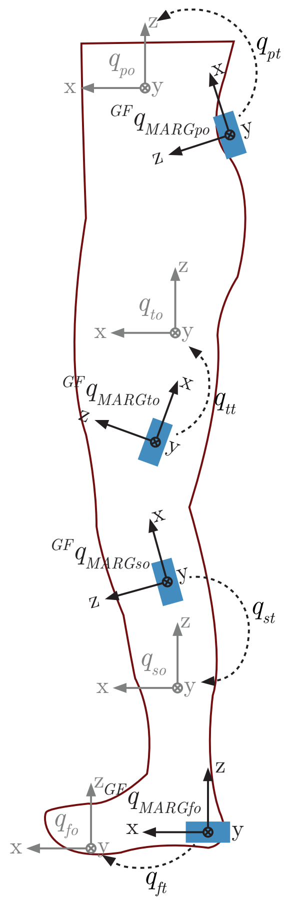


Figure 6.5 MARG sensor orientation transformations.

Using the Hamilton product of the known initial orientations as described using quaternions, the transformation $q_{seg.t}$ of each MARG sensor's initial orientation in the global frame to the initial segment orientation in the global frame could be determined using Equation (6.1), where * denotes the quaternion conjugate.

$$q_{seg.t} = {}^{GF}q^{*}_{seg.o} \otimes {}^{GF}q_{MARG_{seg.o}} \tag{6.1}$$

Segment orientation at each time instance ${}^{GF}q_{seg.k}$ could then be determined by taking the Hamilton product of the quaternion representation of the transformation of each MARG sensor to segment orientation and the orientation of the MARG sensor in the global frame at time instant k using Equation (6.2).

$${}^{GF}q_{seg.k} = {}^{GF}q_{MARG_{seg.k}} \otimes q^{*}_{seg.t} \tag{6.2}$$

Joint angles were calculated as the difference in orientation between a proximal ${}^{GF}q_{seg_1k}$ and distal segment ${}^{GF}q_{seg_2k}$ at each time instant, as described using quaternions (Equation (6.3)). A visual representation of the joint angle (difference in the quaternion orientation) could then be obtained using an Euler angle representation.

$$q_j = {}^{GF}q^{*}_{seg_1k} \otimes {}^{GF}q_{seg_2k} \tag{6.3}$$

### 6.4.6 Spatiotemporal measures

The stride and stance time were estimated using a custom Matlab script, from initial contact (IC) and final contact (FC) points identified from acceleration data using the methods of Jasiewicz, et al. [179]. Stride length estimation was achieved using a zero-velocity update (ZUPT) methodology [181]. The initial orientation estimation of the pelvis sensor was used to determine the foot segment coordinate system and direction of travel using the sensor to segment alignment methodology described above. The acceleration at the heel (minus acceleration due to gravity) was integrated using a trapezoidal approximation to give the velocity of the foot. The drift resulting from the integration of the motional acceleration was corrected by means of a ZUPT. Where a stance phase (and thus known instance of zero velocity) was detected, a Kalman filter was used to reduce the drift caused when integrating by approximating the error in the system. After the ZUPT correction, the stride length could be estimated as the distance travelled between consecutive stance phases.

### 6.4.7 Data analysis and statistical methods

Data were first assessed for normality by visual inspection and a Shapiro Wilks test. The mean absolute percentage error (MAPE) and root mean squared error (RMSE) were calculated for each spatiotemporal and kinematic measure. A classification system was used to assess MAPE values [219], where MAPE ≤ 5% = excellent agreement, 5% < MAPE ≤ 10% = good agreement, 10% < MAPE ≤ 15% = acceptable agreement, and MAPE > 15% = unacceptable agreement. To provide greater insight into the agreement of joint angle estimations throughout the ROM of each repetition, a measure of the percentage of time the MARG method error was within ±10% of the ROM of the OMC system was calculated ($E_{10\%}$). An acceptable error threshold of ±10% for the $E_{10\%}$ calculation was selected to show a clinical difference in means [220]. For time-series comparative measures, MARG joint angle approximations were resampled to 100 Hz and synchronised manually based on the point of maximum flexion throughout a repetition.

Bland–Altman upper and lower 95% limits of agreement (LoA) were used to assess agreement between methods [221, 222]. The LoA were set to 1.96 times the upper and lower standard deviation of the difference between the OMC and MARG method. Where normality was not met, a log transformation was performed prior to undertaking the Bland–Altman analysis. Paired t-tests were conducted between TAF and DEF methods. A Wilcoxon signed-rank test was performed where data were not normally distributed. All statistical analyses were performed in R version 3.6.1 (R Development Core Team, Vienna, Austria), with statistical significance accepted at $p < 0.05$.

## 6.5 Results

### 6.5.1 Kinematic measures

Hip, knee, and ankle joint ROM were compared for IMU and OMC during 195 squat, 195 box squat, and 117 sandbag pickup repetitions, while 193 hip and 195 knee, and 115 hip and 113 knee ROMs were compared for the modified gait and bear crawl, respectively. Marker dropout in the OMC prevented a comparison of hip and knee joints during three crawl strides and two modified gait strides.

Hip and knee joint angle estimation using both the DEF and TAF method showed good to excellent agreement with the OMC system when performing repetitions of the squat, box squat, and sandbag pickup (Table 6.3). The RMSE and MAPE of hip and knee ROM were less for the box squat than the squat when using the TAF MARG method. Bland–Altman plots indicate an underestimation in knee ROM for the squat and sandbag pickup when using the DEF method (Figure 6.6). The underestimation of knee ROM by the MARG method during the squat and sandbag pickup may reflect the large ROM (squat: 121.2 ± 9.5°; sandbag: 126.8 ± 7.2°) compared to the other three exercises. Although there were only three female participants out of the total sample of 13, when comparing data obtained from male and female participants (Figure 6.6), the underestimation in knee ROM during the squat, box squat, and sandbag pickup appeared to be larger in the female group than the combined or male group (DEF method), with such results also being apparent for the TAF method. Where no consistent bias was observed for the combined or male group, a slight overestimation in hip ROM by the MARG method in female participants (both DEF and TAF) may be observed during the squat, box squat, and sandbag pickup. Inconsistencies in the agreement between methods (combined group) were observed for both DEF and TAF methods through the relatively wide Bland–Altman LoA (Figure 6.6).

Ankle joint angle estimations generally showed good agreement with the OMC system when using the DEF method for the squat, box squat, and sandbag pickup (Table 6.3). When using the TAF method, acceptable (sandbag pickup) to unacceptable (squat and box squat) errors were observed. Bland–Altman plots indicate a slight (DEF) to moderate (TAF) overestimation bias in the MARG method for ankle joint ROM during the squat, box squat, and sandbag pickup exercises for the combined group (Figure 6.6). This overestimation (both DEF and TAF) appeared to be slightly smaller in female participants when compared to their male counterparts. Ankle ROM Bland–Altman LoA for the combined group were smallest for the box squat when compared to the squat and sandbag pickup.

In contrast to the squat, box squat, and sandbag pickup, unacceptable agreement at both the hip and knee joint was observed for the shuffle-walk and bear crawl, with the TAF method achieving slightly greater agreeance during the shuffle walk than the DEF method. Preliminary results indicated that a meaningful $E_{10\%}$ analysis of the hip and knee during the shuffle-walk and bear crawl could not be performed, with values ranging from 60.1 ± 23.9 to 78.4 ± 21.2%. This was in part due to the high noise to ROM ratio and slight phase duration discrepancy between the OMC and MARG method, as can be seen in the exemplar data provided in Figure 6.7. No consistent bias was observed for hip and knee ROM in the shuffle-walk and bear crawl (Figure 6.8), with wide LoA in both TAF and DEF methods further demonstrating the inconsistencies in measurements between the OMC and MARG method for hip and knee ROM (Table 6.4).

To an even greater extent than at the hip and knee, preliminary analysis of ankle joint ROM during the shuffle-walk and bear crawl resulted in a high noise to ROM ratio and unacceptably large MAPE. As such, it was determined that a meaningful comparison could not be performed and was omitted (Figure 6.7e,f).

Table 6.3 Kinematic measures and error metrics.

| | OMC | TAF MARG | | | | DEF MARG | | | |
|---|---|---|---|---|---|---|---|---|---|
| | ROM (°) | ROM (°) | RMSE (°) | MAPE (%) | $E_{10\%}$ (%) | ROM (°) | RMSE (°) | MAPE (%) | $E_{10\%}$ (%) |
| Hip | | | | | | | | | |
| Squat | 96.8 ± 11.8 | 100.2 ± 14.9* | 9.8 | 8.2 ± 6.5 | 95.6 ± 8.5 | 95.3 ± 14.3 | 8.8 | 7.6 ± 4.6 | 96.0 ± 7.7 |
| Box squat | 85.5 ± 12.6 | 84.6 ± 14.8* | 7.7 | 6.8 ± 6.1* | 94.4 ± 9.9* | 81.5 ± 13.7 | 8.1 | 8.0 ± 5.1 | 92.2 ± 13.2 |
| Sandbag pickup | 97.1 ± 11.4 | 97.7 ± 14.9* | 9.1 | 7.0 ± 5.5 | 87.4 ± 12.4 | 93.0 ± 13.0 | 9.3 | 7.0 ± 5.7 | 88.1 ± 13.1 |
| Shuffle walk | 12.1 ± 3.3 | 14.1 ± 3.7* | 3.3 | 25.1 ± 21.0* | - | 14.4 ± 3.7 | 3.8 | 28.6 ± 24.7 | - |
| Bear crawl | 33.3 ± 13.5 | 32.9 ± 12.4* | 7.1 | 16.5 ± 21.5 | - | 30.7 ± 12.2 | 7.7 | 16.7 ± 13.4 | - |
| Knee | | | | | | | | | |
| Squat | 121.2 ± 9.5 | 123.8 ± 11.5* | 7.7 | 5.1 ± 3.7* | 100.0 ± 0.4 | 113.0 ± 9.8 | 9.4 | 6.7 ± 3.8 | 100.0 ± 0.5 |
| Box squat | 91.6 ± 9.1 | 91.9 ± 10.8* | 4.4 | 4.0 ± 2.7* | 100.0 ± 0.0 | 84.9 ± 9.6 | 7.2 | 7.4 ± 3.0 | 100.0 ± 0.0 |
| Sandbag pickup | 126.8 ± 7.2 | 126.3 ± 8.5* | 5.9 | 3.7 ± 2.8* | 99.2 ± 3.3 | 118.8 ± 8.8 | 9.2 | 6.4 ± 3.6 | 98.9 ± 3.2 |
| Shuffle walk | 29.1 ± 8.9 | 22.9 ± 8.0* | 6.8 | 22.5 ± 16.5* | - | 21.1 ± 7.4 | 7.9 | 26.0 ± 13.9 | - |
| Bear crawl | 40.0 ± 20.4 | 44.0 ± 20.6* | 8.6 | 28.4 ± 40.6 | - | 36.7 ± 19.0 | 8.4 | 27.3 ± 30.8 | - |
| Ankle | | | | | | | | | |
| Squat | 31.2 ± 5.2 | 37.7 ± 5.7* | 7.2 | 21.9 ± 11.2* | 79.6 ± 15.3 * | 32.3 ± 4.5 | 2.8 | 7.9 ± 6.1 | 93.9 ± 8.3 |
| Box squat | 21.1 ± 4.9 | 26.8 ± 5.4* | 6.6 | 28.6 ± 15.3* | 73.2 ± 15.0 * | 23.0 ± 4.4 | 2.7 | 11.7 ± 7.5 | 89.5 ± 10.3 |
| Sandbag pickup | 38.9 ± 7.4 | 42.9 ± 6.1* | 6.2 | 13.9 ± 11.9* | 84.1 ± 13.4 * | 39.0 ± 5.5 | 3.7 | 8.2 ± 5.7 | 93.8 ± 8.2 |

Values presented as the mean ± standard deviation where relevant. * Significant difference between the TAF and DEF method ($p > 0.05$).

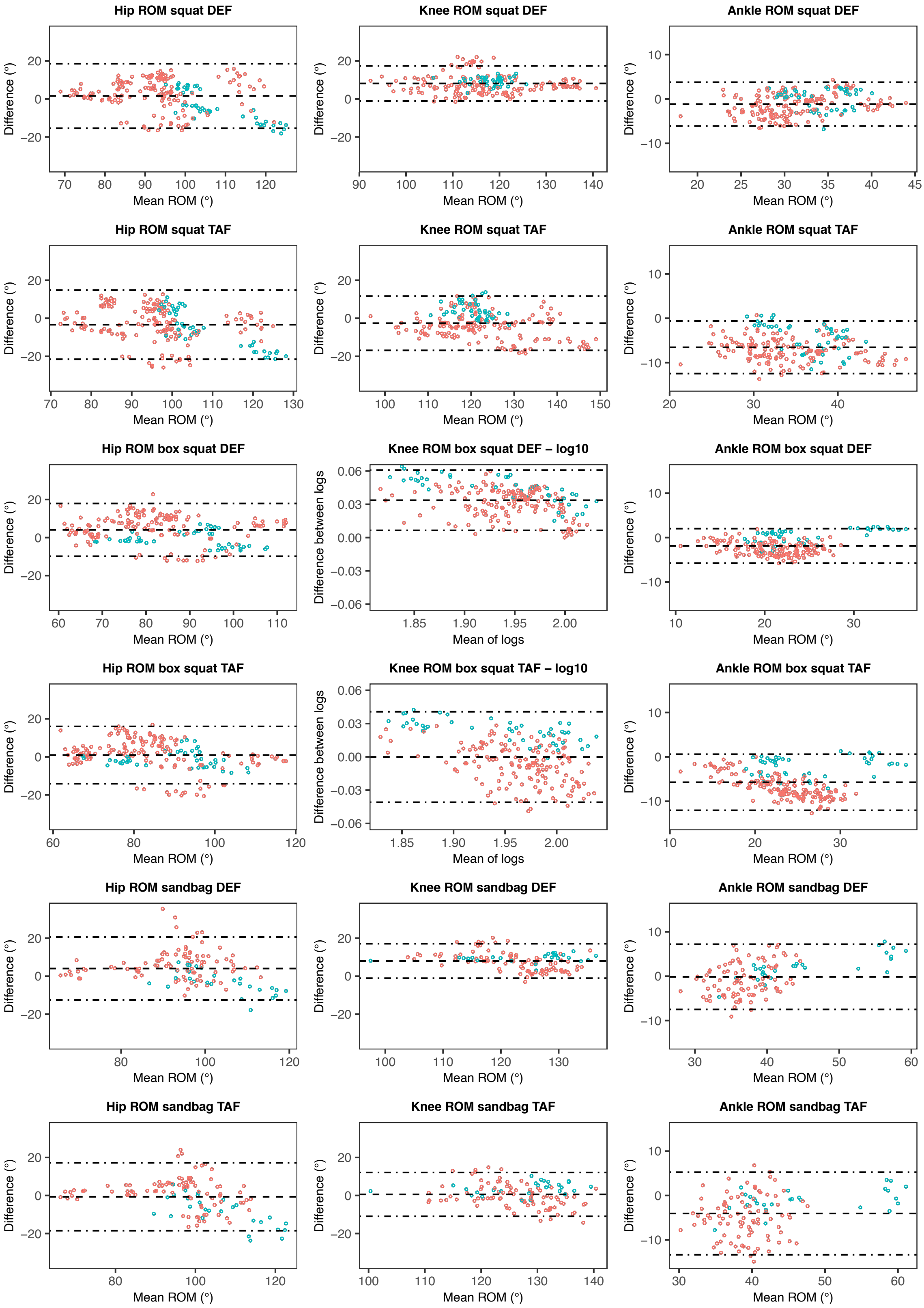


Figure 6.6 Bland–Altman plots for hip, knee, and ankle range of motion (ROM) using each MARG method (DEF/TAF) during the squat (row one/two), box squat (row three/four), and sandbag pickup (row five/six). Red data points represent male participant data, and green data points represent female participant data.

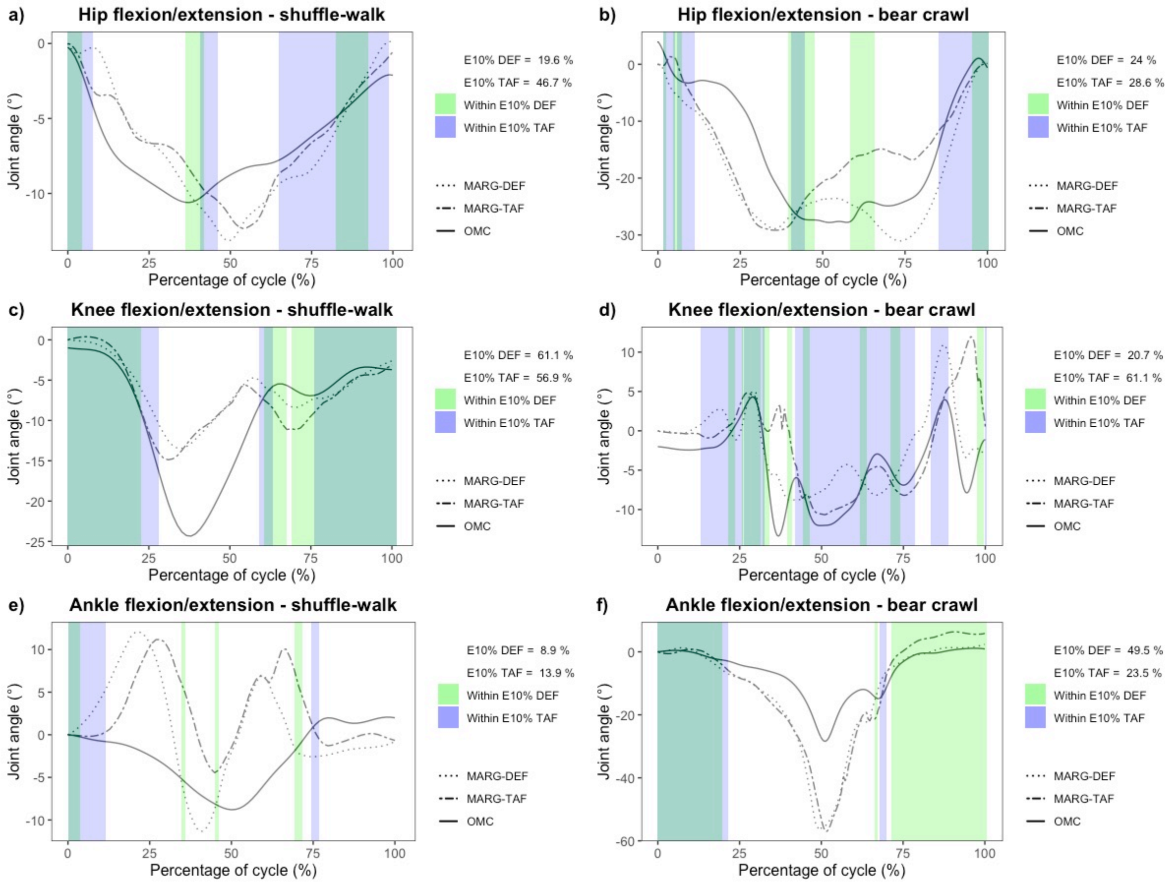


Figure 6.7 Example of preliminary time-series data and $E_{10\%}$ measurement of hip (row one), knee (row two) and ankle (row three) flexion/extension during a single stride of the shuffle-walk (column one) and bear crawl (column two).

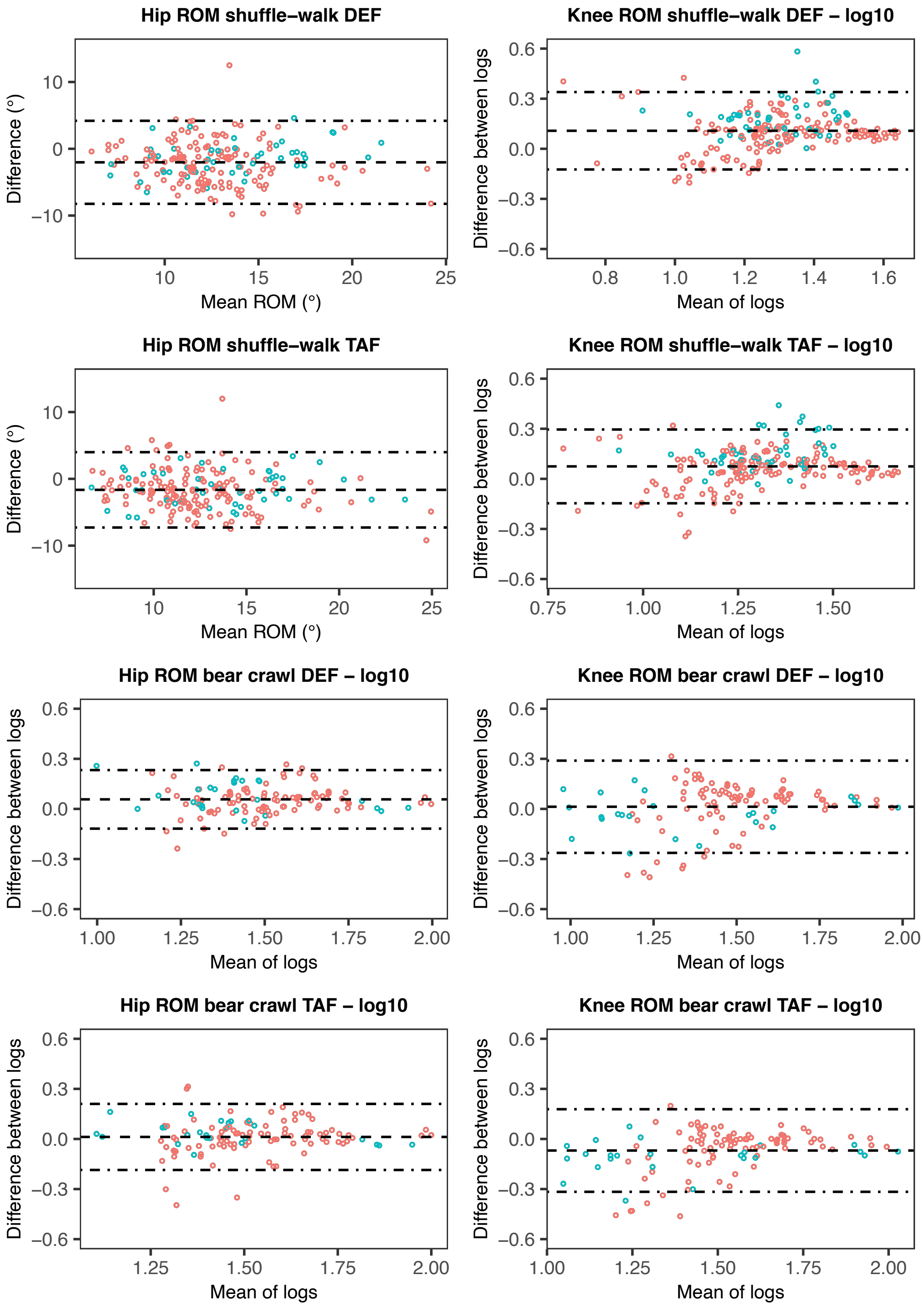


Figure 6.8 Bland–Altman plots for hip and knee ROM using each MARG method (DEF/TAF) during the shuffle-walk (row one/two) and bear crawl (row three/four). Red data points represent male participant data, and green data points represent female participant data.

Table 6.4 Bland–Altman limits of agreement.

| | MARG TAF | | | MARG DEF | | |
|---|---|---|---|---|---|---|
| | L−LoA | Bias | U−LoA | L−LoA | Bias | U−LoA |
| Hip ROM | | | | | | |
| Squat (°) | −21.5 | −3.4 | 14.8 | −15.42 | 1.6 | 18.6 |
| Box squat (°) | −14.1 | 1.0 | 16.0 | −9.8 | 4.1 | 17.9 |
| Sandbag pickup (°) | −18.5 | −0.7 | 17.2 | −12.5 | 4.0 | 20.6 |
| Shuffle−walk (°) | −7.3 | −1.6 | 4.0 | −8.2 | −2.0 | 4.2 |
| Bear crawl | −0.1857* | 0.0123* | 0.2100* | −0.1182* | 0.0572* | 0.2325* |
| Knee ROM | | | | | | |
| Squat (°) | −16.9 | −2.6 | 11.7 | −1.1 | 8.2 | 17.4 |
| Box squat | −0.0409* | −0.0001* | 0.0407* | 0.0065* | 0.0337* | 0.0608* |
| Sandbag pickup (°) | −11.0 | 0.6 | 12.1 | −1.1 | 8.0 | 17.1 |
| Shuffle−walk | −0.1463* | 0.0746* | 0.2954* | −0.1239* | 0.1079* | 0.3398* |
| Bear crawl | −0.3165* | −0.0692* | 0.1781* | −0.2633* | 0.0129* | 0.2891* |
| Ankle ROM | | | | | | |
| Squat (°) | −12.5 | −6.5 | −0.6 | −6.1 | −1.2 | 3.8 |
| Box squat (°) | −12.0 | −5.7 | 0.6 | −5.8 | −1.9 | 2.0 |
| Sandbag pickup (°) | −13.4 | −4.1 | 5.2 | −7.5 | −0.1 | 7.2 |
| Spatiotemporal | | | | | | |
| Stride length (m) | −0.050 | 0.013 | 0.077 | −0.090 | 0.004 | 0.099 |
| Stride time (s) | −0.061 | −0.015 | 0.030 | −0.100 | −0.037 | 0.0256 |
| Stance time (s) | −0.077 | −0.008 | 0.060 | −0.115 | −0.033 | 0.049 |

Positive bias represents underestimation by the MARG method and negative bias represents overestimation by the MARG method; * log transformed data (unitless); **L-LoA**, lower limits of agreement; **U-LoA**, upper limits of agreement.

### 6.5.2 Spatiotemporal measures

The stride length, stride time, and stance times were compared for 192, 178, and 178 instances of the shuffle-walk, respectively, and 116, 83, and 83 instances of the bear crawl, respectively (Table 6.5). The stride length, stride time, and stance time MAPE showed good to excellent agreement with the OMC system (Table 6.6). Bland–Altman plots indicated a slight overestimation of the stride and stance time by the MARG method during both the shuffle-walk and bear crawl, and an underestimation of the stride length by the MARG method during the shuffle-walk (Figure 6.9 and Table 6.6).

Table 6.5 Spatiotemporal measures of the shuffle-walk and bear crawl.

| | OMC | | | MARG | | |
|---|---|---|---|---|---|---|
| | Stride Length (m) | Stride Time (s) | Stance Time (s) | Stride Length (m) | Stride Time (s) | Stance Time (s) |
| Shuffle-walk | 0.339 ± 0.086 | 0.846 ± 0.219 | 0.568 ± 0.179 | 0.326 ± 0.096 | 0.861 ± 0.224 | 0.577 ± 0.177 |
| Bear crawl | 0.515 ± 0.157 | 1.912 ± 0.479 | 1.502 ± 0.497 | 0.511 ± 0.175 | 1.949 ± 0.489 | 1.535 ± 0.500 |

Values presented as the mean ± standard deviation.

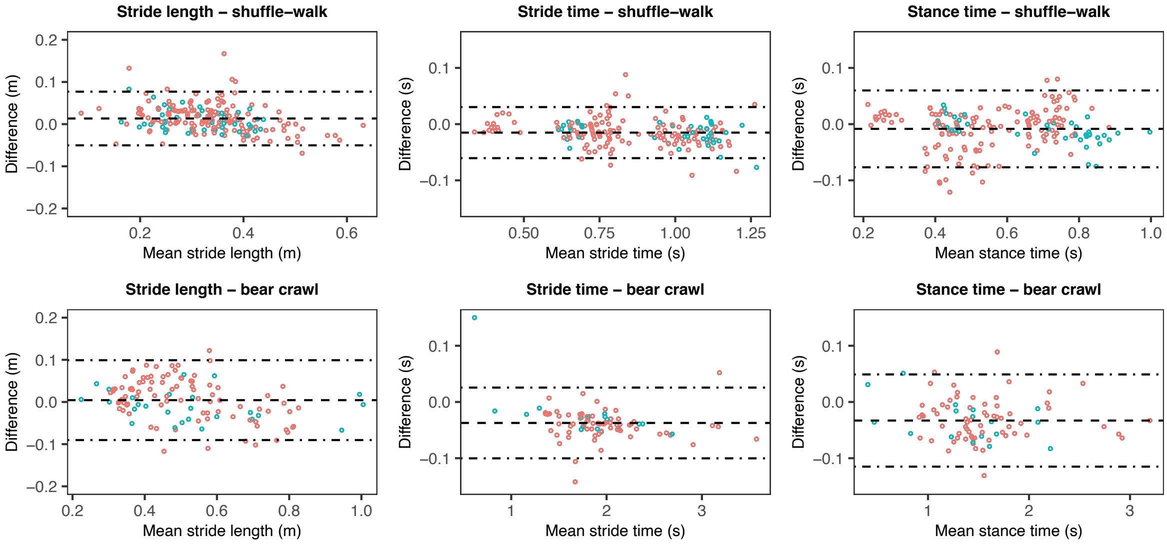


Figure 6.9 Bland–Altman plots for the stride length, stride time, and stance time during the shuffle-walk (row one) and bear crawl (row two). Red data points represent male participant data, and green data points represent female participant data.

Table 6.6 Error metrics of spatiotemporal measures.

| | Stride Length | | Stride Time | | Stance Time | |
|---|---|---|---|---|---|---|
| | RMSE (m) | MAPE (%) | RMSE (s) | MAPE (%) | RMSE (s) | MAPE (%) |
| Shuffle-walk | 0.035 | 8.2 ± 7.9 | 0.028 | 2.6 ± 2.1 | 0.036 | 5.2 ± 5.9 |
| Bear crawl | 0.048 | 7.8 ± 5.7 | 0.049 | 2.4 ± 2.5 | 0.053 | 3.2 ± 2.8 |

Values presented as the mean ± standard deviation where relevant.

## 6.6 Discussion

The aim of conducting this study was to assess the validity of a minimal modelling MARG motion capture method for spatiotemporal and kinematic measures during repetitions of various functional fitness exercises. The MARG method included minimal modelling assumptions, in that simple, sensor to segment alignment, data processing (through the DEF method), and anatomical modelling assumptions were used. To the best of the authors' knowledge, the exercises selected in the current study covered a wider range of sagittal plane ROM than previous literature [142, 145, 205, 223].

The RMSE in hip, knee, and ankle ROM during the squat, box squat, and sandbag pickup were similar to those of previous research during squat, single leg squat, and counter movement jump exercises (hip: 4.9 – 8.3°; knee: 2.4 – 3.1°; ankle: 2.5 – 5.3°) [142]. While the knee ROM RMSE may be slightly greater in the current study than those of Teufl, et al. [142], a MAPE of less than 10% was still considered to be a good level of agreement. Slightly greater agreeance was seen in joint ROM using the TAF method than the DEF method for the hip and knee; however, both methods were acceptable. The DEF method showed greater agreeance in all analysed exercises for ankle ROM and is suggested in preference to the TAF method for ankle joint measures.

The shuffle-walk and bear crawl demonstrated small hip and knee joint ROM (12.1 ± 3.3°–40.0 ± 20.4°) and agreement between the OMC system and both TAF and DEF MARG methods varied. Similar hip and knee RMSE during over-ground walking (hip: 6.1°; knee: 6.8°) have been found in previous studies [224]. The relatively large (>10%) MAPE found during the shuffle-walk and bear crawl movements in the current study suggest neither MARG method (DEF or TAF) may be acceptable for measuring the relatively moderate hip or knee ROM during the shuffle-walk or bear crawl. The high noise to ROM measurements observed in hip and knee ROM during the modified gait patterns (example seen in Figure 6.7d) made the manual alignment of OMC and MARG time-series plots based on peak values ambiguous. Furthermore, phase discrepancies were observed in these data (Figure 6.7a,b), which may be the result of the resampling of MARG joint angle estimations to 100 Hz for comparison with OMC.

In exercises such as the shuffle walk where the stride duration is small (0.846 ± 0.219 s) relative to the sample rate of the OMC system (100 Hz), the modelling of few data points may result in the loss of fidelity in the joint angle approximation. As the MARG method is initially sampled and modelled at 1125 Hz, and then resampled to 100 Hz for comparison with the OMC, the loss of fidelity in the joint angle approximation may be less than the OMC approximation. The large differences observed in the timeseries curve analysis (in particular Figure 6.7e) may be a combined result of the inherent noise in the MARG method joint angle approximation and the loss of fidelity in the OMC joint angle approximation for short-duration activities, such as a stride in the shuffle walk and bear crawl. The noise in the MARG joint angle approximation may be somewhat reduced by refining the parameters selected for the TAF method, while the loss of fidelity in the OMC approximation may be reduced by using an OMC system with greater sampling rate. The ambiguity caused by both noise and phase duration discrepancy led to the inability to confidently report $E_{10\%}$ values for the hip and knee and as such, such data were omitted. It was concluded that the recommendation based on other error metric calculations, that neither MARG method (DEF or TAF) may be acceptable for measuring hip/knee ROM during the shuffle-walk or bear crawl, would not change upon the calculation of $E_{10\%}$ for all participants.

Preliminary ankle ROM data of the shuffle-walk and bear crawl demonstrated an even greater noise to ROM ratio (Figure 6.7e,f) than at the hip and knee. Ambiguity caused by this large noise to ROM ratio lead to the inability to confidently report error metrics. Wells, et al. [45] observed greater differences in OMC- and MARG-based joint angle estimations during higher velocity upper-limb sporting movements when compared to lower velocity movements. As the MARG devices used to measure ankle ROM are positioned closer to the extremity of the lower limb than those used to estimate hip and knee ROM, higher velocities and larger disagreement between the OMC and MARG joint angle estimation than at the hip and knee may be expected. Based on the preliminary data, error metrics of the hip and knee, and predicted greater error metrics at the ankle, it was concluded that neither MARG method may be suitable for ankle ROM assessment during the shuffle-walk and bear crawl where a small ROM and greater movement velocity are expected. The use of different tuning properties, dependent on the sensor location and joint being observed, may assist in reducing the overall error of the system.

Whilst previous researchers have focused on comparing OMC relative angles using markers placed on or around MARG sensors to relative angles estimated from MARG, in the current study, biomechanically-modelled joint estimations derived from an OMC system were compared to relative angles estimated from MARG measures. The relative angles measured using the MARG method assume that the anterior/posterior axis of the foot sensor and the anterior/posterior axes of all limbs are aligned during the calibration pose. Any error in the initial alignment will be apparent in the mathematical transformation of each individual segment sensor coordinate system to the respective segment coordinate system, with the error compounding where adjoining segments are misaligned. Brice, et al. [127] demonstrated less agreement between OMC biomechanically-modelled joint angles and un-modelled MARG relative angles than OMC un-modelled relative angles and MARG measured relative angles. This leads to the suggestion that some of the differences in joint angle ROM estimations found in the current study may be due to the differences in modelling assumptions used in each of the OMC and MARG methods and the compounding error occurring throughout the alignment and mathematical transformation process.

With the exception of the stride length, the errors in spatiotemporal measures during the shuffle-walk and bear crawl in the current study were greater than those observed using a similar methodology during over-ground walking [141]. The stride length, stride time, and stance time RMSE observed by Teufl, et al. [141] during over-ground walking were 0.04 m, 0.01 s, and 0.02 s, respectively, with similar RMSE having been observed in treadmill running [225]. The larger disagreement in temporal parameters between the OMC and MARG method in the current study may partially be due to the difficulty in identifying the instance of IC and FC during the modified gait patterns, which resulted in reduced IC and reduced changes in heel acceleration during the initial swing than would be seen in a normal gait with longer strides [185]. In the modified gait patterns, identifying FC from a MARG sensor mounted on the lateral side of the heel, where the toe is the last true contact point with the ground, may lead to inaccuracies in identifying the FC instance.

While a number of gaps within the literature were addressed in this study, the limitations of the current study should be noted. Data were only collected from a single side of the body, in a limited laboratory space and assessed only for sagittal plane flexion/extension ROM. Although a magnetic calibration was conducted for each testing session, it is expected that due to ferromagnetic disturbances present in the laboratory environment, the accuracy of the MARG method may have still been compromised. The reference OMC and MARG method use different physical measurements to derive joint angle estimations, with each method having associated noise. Measurement noise combined with different modelling assumptions would result in distinctly different noise properties and therefore signal patterns. The ability to compare estimations of small ROM between systems where the noise to signal ratio is high may be a major limitation when validating MARG against OMC methods [142, 145].

## 6.7 Future work

To further develop the proposed MARG method into an accurate means of measuring human kinematics during high velocity, small ROM movements, such as the shuffle walk and bear crawl, a number of areas of potential development are suggested. Further refinement of the Kalman filter tuning parameters, specialised for a given exercise (variance of accelerometer/gyroscope noise, and linear acceleration compensation factor) and the environment (magnetometer disturbance noise) may be needed to improve joint ROM estimations where high signal to noise ratios are observed [147]. These parameters may be established through further data collection and testing. Where previous literature has achieved segment coordinate system to sensor alignment using specialised equipment [45] or complicated movement-based algorithms [150, 152, 172, 175], a possible middle-ground between the complexities of previous literature and the minimal methods used in the current study may be achieved. Although not a direct development of the MARG method, collecting data at a sampling rate common to both MARG and OMC equipment will likely result in greater agreeance between methods and provide a closer measure to the true validity of the MARG method. Future work should also look at assessing the validity of the MARG method for bilateral, multi-planar motion and assess its inter-day and assessor reliability.

## 6.8 Conclusions

The proposed minimal modelling MARG-based method is a valid means of assessing spatiotemporal and kinematic measures of persons performing various functional fitness exercises. It is suggested that care should be taken when selecting tuning and filtering parameters when using the MARG method for specific exercises. Although a high noise to joint ROM measurement ratio may be an inherent issue when assessing the validity of human motion analysis methods during some exercises, further development of the MARG method may result in a valid means of measuring small joint ROM during fast movements.

# CHAPTER 7:

# EXPERIMENTAL STUDY 1

# 7. The biomechanical characteristics of the strongman yoke walk

## 7.1 Preface

The systematic reviews presented in Chapter 2 and Chapter 3 identified the lack of spatiotemporal and kinematic analyses of athletes performing the yoke walk as a major gap in the current field of strongman biomechanics research. Further, all previous strongman biomechanics studies had only included male athletes with a variety of training backgrounds, some with little to no strongman training or competition experience. The study presented in this chapter describes the general movement pattern of experienced male and female strongman athletes performing the yoke walk using ecologically valid loads and carry distances. Part a) of Question 4, Question 5 and Question 6 were addressed in this chapter.

Supplementary tables (e.g., Table S1) referenced throughout this chapter can be found in Appendix 5.

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## 7.2 ABSTRACT

The yoke walk is a popular strongman exercise where athletes carry a heavily loaded frame balanced across the back of their shoulders over a set distance as quickly as possible. The aim of conducting this study was to use ecologically realistic training loads and carry distances to: 1) establish the preliminary biomechanical characteristics of the yoke walk; 2) identify any biomechanical differences between male and female athletes performing the yoke walk; and 3) determine spatiotemporal and kinematic differences between stages (intervals) of the yoke walk. Kinematic and spatiotemporal measures of hip and knee joint angle, and mean velocity, stride length, stride rate and stance duration of each 5 m interval were taken whilst 19 strongman athletes performed three sets of a 20 m yoke walk at 85% of their pre-determined 20 m yoke walk one repetition maximum. The yoke walk was characterised by flexion of the hip and slight to neutral flexion of the knee at heel strike, slight to neutral extension of the hip and flexion of the knee at toe-off and moderate hip and knee range of motion (ROM), with high stride rate and stance duration, and short stride length. Between-interval comparisons revealed increased normalised stride length (high velocity: $1.300 \pm 0.198$; low velocity: $1.140 \pm 0.160$; $-0.97 \leq d \leq -0.80$; $p < 0.001$), stride rate (high velocity: $0.498 \pm 0.053$; low velocity: $0.476 \pm 0.052$; $-0.47 \leq d \leq 0.43$; $p < 0.001$) and lower limb ROM, and decreased stance duration (high velocity: $0.411 \pm 0.056$; low velocity: $0.441 \pm 0.057$; $0.60 \leq d \leq 0.69$; $p < 0.001$) at greater velocity. Although no main between-sex differences were observed, two-way interactions revealed female athletes exhibited greater knee extension at toe-off ($\eta_p^2 = 0.048$, $p = 0.022$) and reduced hip ROM ($\eta_p^2 = 0.048$, $p = 0.020$) during the initial (0 – 5 m) when compared with the final three intervals (5 – 20 m), and covered a greater distance before reaching maximal normalised stride length than males. The findings resulting from conducting this study may better inform strongman coaches, athletes and strength and conditioning coaches with the biomechanical knowledge to: provide athletes with recommendation on how to perform the yoke walk based on the technique used by experienced strongman athletes; better prescribe exercises to target training adaptations required for improved yoke walk performance; and better coach the yoke walk as a training tool for non-strongman athletes.

## 7.3 INTRODUCTION

Strongman is a competitive strength-based sport which now caters to both male and female athletes of varying age, body mass and physical ability. Strongman exercises are often derived from traditional tests of strength and involve more awkward variations of weightlifting/powerlifting exercises. Such exercises include variations of the squat, deadlift and clean and jerk and heavier versions of common everyday activities such as loaded carries [51]. While strongman exercises vary across competitions, the most common exercises often require athletes to: lift stones, axles, kegs, sandbags or oversized dumbbells for maximal load or as a set of incremental loads in the shortest time; pull heavy vehicles or flip large vehicle tyres over a distance in the shortest time; or carry loaded frames, kegs or sandbags from one location to another in the shortest time [13].

The strongman yoke walk requires an athlete to carry a heavily loaded frame balanced across the back of the shoulders a set distance, often 20 m (Figure 7.1). In strongman training and competition, the yoke walk is typically the heaviest load carriage exercise performed by athletes. The winner of events like the yoke walk, in a competition setting, is the athlete who requires the shortest time to complete the set distance. For those athletes unable to complete the set distance, the distance the yoke was moved from the original starting position is the performance measure [226].

Research on the biomechanics of the yoke walk is limited. McGill, et al. [36] measured trunk muscle activation patterns and lumbar spine motion, load and stiffness of three experienced male strongman athletes (body mass: 117.3 ± 27.5 kg) performing a single 8 m yoke walk loaded at 177.3 ± 24.3 kg. The large spinal compression observed in athletes performing the yoke walk was suggested to be the result of the greater absolute load of the yoke (when compared with all other implements used in the study including the farmers walk, log lift, tyre flip and atlas stone lift) and the large torso muscular co-contraction required to produce spinal stability throughout the walk [36]. Beyond the limitation of only including three participants in their study, the loads and carry distance used in the study by McGill, et al. [36] would be considered quite easy by today's standards, whereby athletes of this body mass may be expected to carry loads in excess of 300 kg for at least twice the distance (e.g. 15 – 20 m) in competition.


Figure 7.1 A strongman athlete performing the yoke walk. Image reproduced with permission from respective copyright owner and person pictured.

A retrospective injury study conducted by Winwood, et al. [14] revealed 8% of injuries in strongman athletes were caused by the yoke walk, with the most common site of injury during the yoke walk being the lower back. Such findings identified the yoke walk as the second most dangerous strongman exercise with respect to injury causation out of the most popular strongman exercises, with the most dangerous being the atlas stone lift [14]. The greater loads routinely carried by athletes in yoke walk training and competition than in the previous yoke walk study by McGill, et al. [36], coupled with the retrospective data by Winwood, et al. [14], suggest that athletes are likely exposed to even greater spinal muscular compression and thus greater injury risk than first anticipated by McGill, et al. [36].

Due to the lack of quantitative data on the yoke walk, the biomechanics of loaded backpack carriage and the strongman farmers walk exercise, where competitors are required to carry a heavy object (similar to a suitcase) in each hand, may provide some insight into the likely biomechanics of the yoke walk [217]. Differences in lower limb joint kinematics at heel strike and toe off and joint range of motion (ROM) measures have been observed between the farmers walk and unloaded walk [5]. As the farmers walk was characterised by greater flexion of each lower limb joint at heel strike, when compared with unloaded walking, it was concluded that the adopted strategy may reduce braking forces and put the muscle in a better position for force development [5]. Both the farmers walk and backpack load carriage have been associated with an increase in stride rate and a decrease in stride length when compared with unloaded walking, with larger effect sizes reported at greater loads [5, 98].

No data exists comparing the biomechanics of male and females performing the yoke walk or in carrying loads similar to those commonly carried in the yoke walk. Biomechanical differences between male and females carrying sub-body mass loads have been reported. When walking at the same velocity (~1.78 m/s) and carrying the same absolute load (≤ ~36 kg distributed as various sites on the body including a rucksack), females exhibited greater forward inclination of the trunk and employed greater stride rate to compensate for their shorter stride length than males [227]. Martin, et al. [227] concluded that females were more sensitive to load than males, with biomechanical differences suggested to be due to the differences in anthropometrics between sexes. Bode, et al. [228] also reported between-sex differences where male soldiers were found to exhibit greater knee ROM than female soldiers when carrying the equivalent absolute vest-borne load (≤ 55 kg) at a set velocity (1.34 m/s). Conversely, Silder, et al. [229] and Krupenevich, et al. [230] found no biomechanical differences between male and females undertaking sub-body mass load carriage, with Krupenevich, et al. [230] concluding that insufficient loading (22 kg) may have accounted for the lack of significant between-sex biomechanical differences.

The between-sex studies of Martin, et al. [227], Bode, et al. [228] and Krupenevich, et al. [230] used identical absolute loads for male and female participants, whereas Silder, et al. [229] used loads based on a percentage of the carrier's body mass. The loading conditions used by Silder, et al. [229] may be more representative of the differences in loads used by male and female athletes performing the yoke walk. Conducting between-sex comparative analyses where males and females are matched for strength (which may also be achieved through appropriate loading) is particularly important when determining the true effect of sex on the movement pattern of an athlete, as strength and skill level are possible confounding factors in this observation [231].

The initial acceleration phase (0 – 3 m) of the farmers walk has been associated with reduced stride lengths, stride rates and increased stance duration and smaller thigh and knee ROM, when compared with the later stages of the walk (8.5 – 20 m) [30]. Due to the lack of between-sex biomechanical analyses performed for heavy load carriage exercises such as the farmers walk or yoke walk, and the inconclusive biomechanical differences between male and female athletes carrying sub-body mass loads [227-230], it is unknown if any two-way interactions exist between sex and interval during heavy load carriage.

As this study is the first of its kind to present spatiotemporal and kinematic measures of male and female athletes performing the yoke walk, an emphasis is placed on the importance of undertaking a descriptive-type study of the movement pattern associated with the yoke walk. The aim of conducting this study is to use ecologically realistic training loads and carry distances to: 1) establish the preliminary biomechanical characteristics of the yoke walk; 2) identify any biomechanical differences between male and female athletes performing the yoke walk; and 3) determine spatiotemporal and kinematic differences between stages (intervals) of the yoke walk. In alignment with the aim of conducting this study, it was hypothesised that: 1) athletes performing the yoke walk would exhibit reduced lower limb ROM, stride length and stance duration and increased stride rate when compared with data of the previously studied farmers walk; 2) no between-sex differences would be observed; and 3) athletes would exhibit smaller joint ROM, smaller stride length, reduced stride rate and greater stance duration during the initial 5 m than the later intervals.

Addressing the aim of this study will enable researchers, strongman coaches and strength and conditioning coaches to: provide male and female strongman athletes with a more informed recommendation on how to perform the yoke walk based on the technique used by experienced strongman athletes; conceptualise technique improvements for performance enhancement; better identify possible injury risks associated with performing the yoke walk; prescribe the use of the yoke walk as a training tool for both strongman and non-strongman athletes with greater directed intent; and construct future research into the strongman yoke walk.

## 7.4 MATERIALS AND METHODS

### 7.4.1 EXPERIMENTAL APPROACH

A cross-sectional observational experimental design was used to establish spatiotemporal and kinematic biomechanical characteristics throughout a 20 m yoke walk. Male and female strongman athletes (Table 7.1) undertook two testing sessions. Session one consisted of a determination of the athlete's 20 m yoke walk one repetition maximum (1RM) to establish loading conditions for session two. Session two consisted of the collection of spatiotemporal and kinematic measures during three sets of 20m yoke walks with 85% 1RM load. Anthropometric measures of stature, body mass, trochanterion-tibiale laterale height and tibiale laterale height of each athlete were taken by a trained person using ISAK methodologies [232].

### 7.4.2 PARTICIPANTS

Nineteen experienced strongman competitors (12 male and 7 female) were recruited for this study (Table 7.1). All participants were required to have a minimum of 18 months' strongman training experience, have competed in at least one strongman competition and be free from moderate or major injury for a minimum of one week before testing. For the purposes of the study a moderate injury was defined as an injury that had stopped the athlete from performing a strongman exercise during a strongman session, whereas a major injury was defined as an injury which had stopped the athlete continuing all exercises/the session completely [13]. Participants who met the above criteria were informed of the purpose of the study and asked to sign an informed consent form. Ethical approval was granted for all procedures used throughout this study by Bond University's Human Research Ethics Committee (BH00045).

Table 7.1 Participant characteristics.

| Descriptor | Female | Male |
|---|---|---|
| Age (y) | 33.1 ± 6.7 | 30.3 ± 6.8 |
| Body mass (kg) | 81.1 ± 14.5 | 111.5 ± 26.8 |
| Stature (m) | 1.65 ± 0.04 | 1.82 ± 0.09 |
| Femur length (m) | 0.394 ± 0.032 | 0.420 ± 0.040 |
| Tibia length (m) | 0.475 ± 0.022 | 0.519 ± 0.030 |
| Max 20 m yoke (kg) | 170.0 ± 44.0 | 270.0 ± 41.6 |
| 85% 1RM yoke (kg) | 144.5 ± 37.4 | 229.5 ± 35.3 |
| Strongman training experience (years) | 2.5 ± 1.0 | 2.9 ± 1.7 |
| Strongman competition experience (number of competitions in past 2 years) | 4.0 ± 3.0 | 3.4 ± 2.2 |

### 7.4.3 Trial conditions

Athletes were instructed to prepare for each session in the same way in which they would prepare for a training session to achieve optimal performance in the testing sessions. As athletes were well trained in strongman, self-directed warm-up routines were performed by each participant [5, 31, 32, 69, 233]. Warm-up routines typically lasted for 15 - 30 min and included dynamic stretching and short distance (< 10 m) yoke walks at loads approaching those expected to be used by the individual throughout the session. Athletes were permitted to use knee and elbow sleeves, lifting belts, wrist wraps and lifting chalk during sessions, as these lifting aids are commonly used in training and competition.

### 7.4.4 Session protocols

Session one 1RM testing required athletes to carry a maximal load yoke a distance of 20 m in under 20 s without dropping (returning the yoke to the ground) during the walk. Athletes worked up to a maximum yoke load in increments selected by the athlete. When an athlete was unable to complete the distance in under 20 s, or dropped the yoke before finishing the 20 m, the athlete was permitted one additional attempt at the failed load. Where the athlete failed the second attempt, the previous successfully completed load was prescribed as their 1RM. Athletes were assigned a rest period of six to eight min between each attempted load [55].

Session two was performed a minimum of seven days after session one and required athletes to perform three sets of a 20 m yoke walk as quickly as possible at a load of 85% of their 1RM from session one. This load was selected to reflect a typical training session routinely performed by the strongman athletes, whereby they typically select heavy, submaximal loads with the intention of performing multiple sets with high velocity and no drops. To begin the trial the athlete was positioned standing beneath the cross member of the yoke with the yoke still in contact with the ground, as would be the typical starting position in a strongman competition. On the signal "athlete ready, three, two, one, lift" the athlete lifted the yoke from the ground and commenced the 20 m walk. The trial was concluded as soon as the final timing gate was broken at the 20 m line. Where an athlete dropped the yoke during a set, data were only included from the previously completed 5 m intervals within that set. Athletes were assigned a rest period of six to eight min between each set [55].

#### 7.4.5 DATA ACQUISITION AND ANALYSIS

Yoke walks were performed indoors on a 20 m rubberised/synthetic floored runway. Dimensions of the yoke were 1.58 m (length), 1.38 m (width), 2.08 m (height), with an adjustable crossmember to suit the stature of each athlete. Kinematic and spatiotemporal measures of athletes performing the yoke walk were estimated using the inertial motion capture methodologies of Hindle, et al. [140] (Table 7.2). Four magnetic, angular rate and gravity (MARG) devices (ImeasureU, Vicon Motion Systems Ltd., Oxford, UK) were positioned on the athlete as detailed in Table 7.3, capturing tri-axial acceleration, angular velocity and magnetic field strength data at 1125 Hz (accelerometer and gyroscope) and 112 Hz (magnetometer) [140]. The MARG data collected for each segment were input into a Matlab script (The Mathworks Inc., Natick, MA, USA) developed by the authors to estimate hip and knee joint kinematics in the sagittal plane, and stride length, stride rate and stance duration [140].

Timing gates (Smartspeed, Fusion Sport, Queensland, Australia) were positioned at the 0 m (start), 5 m, 10 m, 15 m and 20 m (finish) mark of the runway (Figure 7.2) to measure split times for each 5 m interval. All velocity measures reported throughout were based on timing gate calculations. At the beginning of each trial the yoke was positioned behind the 0 m mark so that the first timing gate would be broken within the first stride made by the athlete. An iPad Air 2 (iPad Air 2, iOS 13.3.1, Apple Inc., CA, USA) recording at 120 Hz was used to capture and count complete strides within each 5 m interval. The video data were used to identify strides from each interval in the time-series MARG-based spatiotemporal and kinematic estimations (Table 7.2). Spatiotemporal measures of mean velocity, stride length, stride rate and stance duration were normalised using a Froude number approach to account for between-athlete (especially, between-sex) differences in lower limb length and inertial properties [234, 235]. Only normalised spatiotemporal measures were included in the statistical analysis. Non-normalised values are provided in the supplementary tables.

Table 7.2 Temporal and kinematic measurement definitions.

| Parameter | Definition |
|---|---|
| Spatiotemporal | |
| Mean velocity (m/s) | Distance of the walk interval (5 m) divided by the time taken to complete the given interval. |
| Stride rate (Hz) | Inverse of the time for each stride. |
| Stride length (m) | Horizontal distance covered from heel strike to the next heel strike of the same foot. |
| Stance duration (s) | Duration of time from heel strike to toe-off of the same foot. |
| Kinematic | |
| Joint angle (º) | Hip and knee angle at heel strike and toe-off. Joint angle definitions provided in Figure 7.3. Positive angles denote flexion, negative angles denote extension. |
| Hip ROM (º) | Maximum angle between the pelvis and thigh minus minimum angle between the pelvis and thigh throughout a stride. |
| Knee ROM (º) | Maximum angle between the thigh and shank minus minimum angle between the thigh and shank throughout a stride. |

*ROM* range of motion.

Table 7.3 MARG device locations.

| Segment | Position |
|---|---|
| Pelvis | Halfway between the left and right posterior superior iliac spine. |
| Right thigh | 150 mm proximal to the lateral epicondyle of the femur. |
| Right shank | 100 mm distal to the lateral tibial condyle. |
| Right foot | Midway between the base of the foot and the lateral malleoli. |

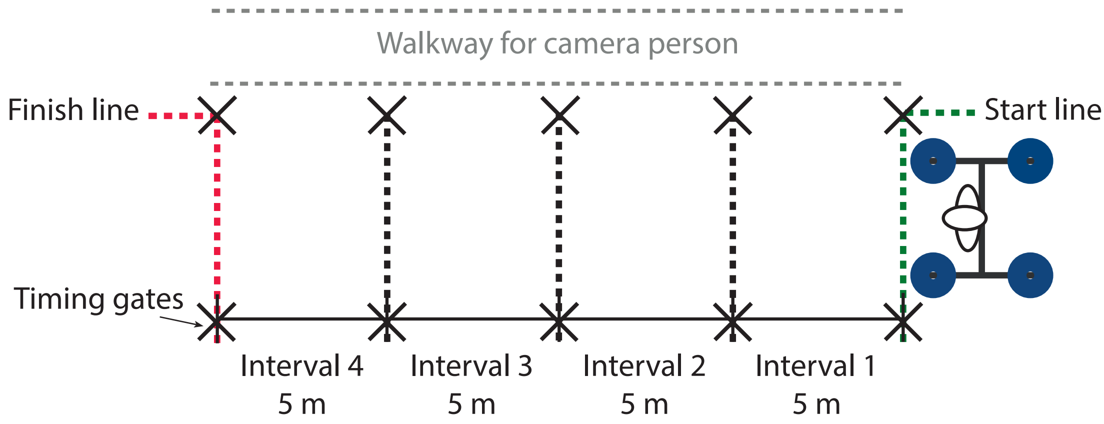


Figure 7.2 Runway and equipment schematic.

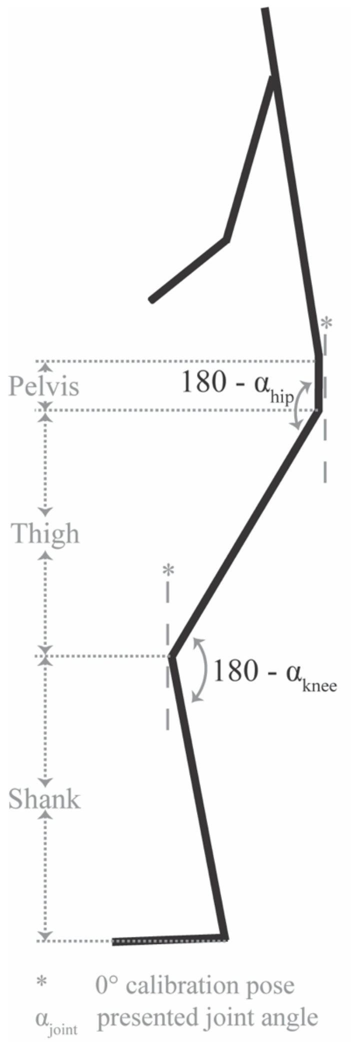


Figure 7.3 Joint angle definitions.

### 7.4.6 Statistical methods

Descriptive statistics (mean ± standard deviation) of all variables were calculated for each 5 m interval of the 20 m walk. A linear mixed effects model with post-hoc analyses was used to establish two-way interactions between sex and interval for each biomechanical measure and main effects of sex, interval and set. Each individual athlete was classified as a random effect. The modelled data was assessed for main effects of set prior to combining measured parameters for all sets. Partial eta-squared effect sizes ($\eta_p^2$) were calculated for two-way interactions with classifications of negligible ($\eta_p^2 \leq 0.01$), small ($0.01 > \eta_p^2 \geq 0.06$), moderate ($0.06 > \eta_p^2 \geq 0.14$) and large ($\eta_p^2 > 0.14$) [236]. Bonferroni post-hoc pairwise t-tests were conducted on parameters where significant differences were detected. Cohen's d (d) effect sizes were calculated for pairwise comparisons with classification of negligible ($d < 0.2$), small ($0.2 \leq d < 0.5$), moderate ($0.5 \leq d < 0.8$) and large ($d \geq 0.8$) [236]. Data were checked for normality and homoscedasticity using visual inspection. Power analyses were conducted based on the limited farmers walk data available [30]. Expected between-interval differences indicated a total population of 17 athletes would be required to attain a study of 80% power with a Type I error of < 5%. Based on previous between-sex data of load carriage [228, 229], significant, albeit small and in some cases no between-sex differences were reported. Using the data of Bode, et al. [228], in which significant between-sex differences in knee joint ROM were observed during load carriage (≤ 55 kg), a sample size of approximately 16 male and 16 female strongman athletes would be required to attain a study of 80% power with a Type I error of < 5%. All statistical analyses were performed in R version 3.6.1 (R Development Core Team, Vienna, Austria), with statistical significance accepted at $p = 0.05$.

## 7.5 RESULTS

A total of 854 strides were collected across all participants and trials, providing data of 854 and 839 strides for the hip and knee, respectively. The failure to analyse knee joint kinematics for all strides was attributed to sensor malfunction (n = 15). Spatiotemporal measures were collected for all 854 complete strides. Data were omitted from interval two (n = 1), interval three (n = 1) and interval four (n = 2), where participants (n = 2) dropped the yoke during a set. Anthropometric measures of stature ($d = 2.59$, $p < 0.001$), body mass ($d = 1.41$, $p = 0.005$) and lower limb length ($d = 1.35$, $p = 0.009$) statistically differed between male and female athletes, therefore all relevant variables were normalised to remove lower limb anthropometric effects.

### 7.5.1 GENERAL BIOMECHANICAL CHARACTERISATION

Mean and standard deviation of the kinematic and spatiotemporal measures for the entire yoke walk are presented in Table 7.4. Notable kinematic characteristics of the yoke walk included: flexion of the hip and slight to neutral flexion of the knee at heel strike; and slight to neutral extension of the hip and flexion of the knee at toe-off (Figure 7.4, Table S1). Statistically significant differences in hip and knee joint angles between heel strike and toe off events were supported by large effect sizes (hip: $d = 3.53$, $p < 0.001$; knee: $d = 5.08$, $p < 0.001$) (Table S2). No statistically significant main effect between-sex differences were observed for both kinematic and spatiotemporal measures ($0.004 \leq \eta_p^2 \leq 0.118$, $p \geq 0.15$) (Table 7.4, Table S4).

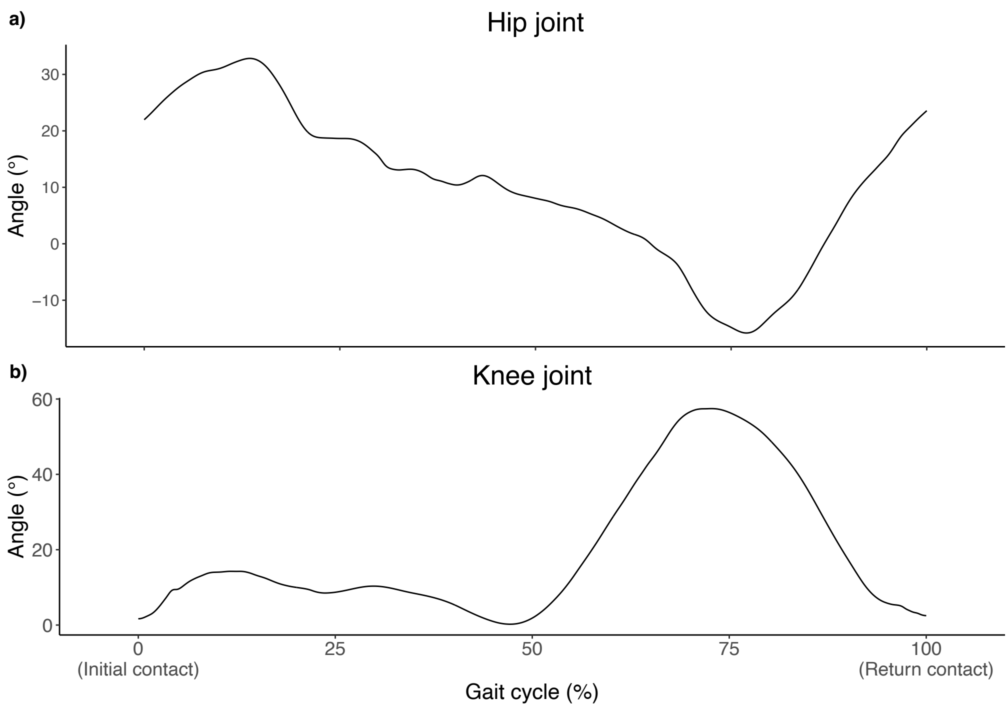


Figure 7.4 a) hip joint angle; and b) knee joint angle exemplar data for a single gait cycle of the yoke walk. Flexion denoted by a positive angle and extension denoted by a negative angle.

Table 7.4 Spatiotemporal and kinematic interval independent mean ± SD measures of the yoke walk.

| | Male | Female | Group |
|---|---|---|---|
| Spatiotemporal | | | |
| Mean velocity (m/s) | 1.649 ± 0.367 | 1.770 ± 0.326 | 1.694 ± 0.356 |
| Normalised mean velocity | 0.546 ± 0.121 | 0.604 ± 0.111 | 0.567 ± 0.121 |
| Stride length (m) | 1.127 ± 0.174 | 1.155 ± 0.164 | 1.138 ± 0.171 |
| Normalised stride length | 1.211 ± 0.187 | 1.320 ± 0.188 | 1.252 ± 0.194 |
| Stance duration (s) | 0.435 ± 0.061 | 0.389 ± 0.040 | 0.417 ± 0.058 |
| Normalised stance duration | 1.410 ± 0.198 | 1.303 ± 0.135 | 1.370 ± 0.184 |
| Stride rate (Hz) | 1.586 ± 0.201 | 1.670 ± 0.123 | 1.617 ± 0.180 |
| Normalised stride rate | 0.489 ± 0.062 | 0.499 ± 0.037 | 0.492 ± 0.054 |
| Hip | | | |
| Initial contact (º) | 23.4 ± 6.8 | 24.3 ± 7.5 | 23.8 ± 7.1 |
| Toe-off (º) | -2.9 ± 7.5 | -3.8 ± 9.2 | -3.2 ± 8.2 |
| Range of motion (º) | 36.5 ± 7.7 | 40.4 ± 7.3 | 37.9 ± 7.8 |
| Knee | | | |
| Initial contact (º) | 6.7 ± 4.8 | 4.0 ± 4.0 | 5.7 ± 4.7 |
| Toe-off (º) | 46.2 ± 8.6 | 45.4 ± 12.3 | 45.9 ± 10.2 |
| Range of motion (º) | 54.6 ± 10.0 | 52.7 ± 11.7 | 53.9 ± 10.7 |

### 7.5.2 Between-interval biomechanical differences – sex independent (main effect)

A number of statistical between-interval joint kinematic and spatiotemporal differences were observed (Figure 7.5 and Table S1). Small to large effect sizes were presented for knee joint angle at heel strike ($0.69 \leq d \leq 0.96$, $p < 0.001$), hip joint angle at toe-off ($0.69 \leq d \leq 0.93$, $p \leq 0.001$) and knee ROM ($-0.64 \leq d \leq -0.36$, $p < 0.001$) between combinations of the first interval and later three intervals (Table S3). For normalised spatiotemporal parameters, athletes exhibited statistically smaller stride length ($-0.97 \leq d \leq -0.80$, $p < 0.001$), stride rate ($-0.47 \leq d \leq -0.43$, $p < 0.001$) and mean velocity ($-1.53 \leq d \leq -1.42$, $p < 0.001$), and increased stance duration ($0.60 \leq d \leq 0.69$, $p < 0.001$) in the initial interval when compared with the final three intervals (Figure 7.6), with effect sizes generally ranging from small to large (Table S1 and Table S3).

### 7.5.3 Between-interval biomechanical differences – sex dependent (two-way interaction)

Small effect sizes were observed for two-way interactions between sex and interval for measures of knee angle at toe-off ($\eta_p^2 = 0.048$, $p = 0.022$), hip ROM ($\eta_p^2 = 0.048$, $p = 0.020$) and normalised stride length ($\eta_p^2 = 0.040$, $p = 0.045$) (Table S4). Female athletes exhibited significantly greater knee extension at toe off during the initial interval when compared with the final two intervals ($0.66 \leq d \leq 0.79$, $0.001 \leq p \leq 0.008$) and reduced hip ROM during the initial interval when compared with the final three intervals ($-0.97 \leq d \leq -0.62$, $0.001 < p \leq 0.006$), whereas male athletes did not display these between-interval differences (Table S1, Table S3 and Figure 7.5). In addition to the statistically smaller normalised stride length observed during the initial interval when compared with the final three intervals observed for male and female athletes, female athletes also displayed smaller normalised stride length during interval two when compared with interval four ($d = -0.373$, $p = 0.033$) (Figure 7.6).

### 7.5.4 Between-set biomechanical differences

Between-set analysis was performed for the purpose of identifying any potential effects of set number (possibly indicative of fatigue) on athlete biomechanics. A number of statistical between-set biomechanical differences were observed for the combined group (Table S6). Pairwise comparisons revealed between-set differences to be primarily between sets one and three, with all differences being of a negligible to small effect size ($-0.47 \leq d \leq 0.16$, $0.001 \leq p \leq 0.04$) (Table S7 and Table S8). Due to the negligible to small effect sizes observed for between-set differences, data from each set were combined for all analyses.

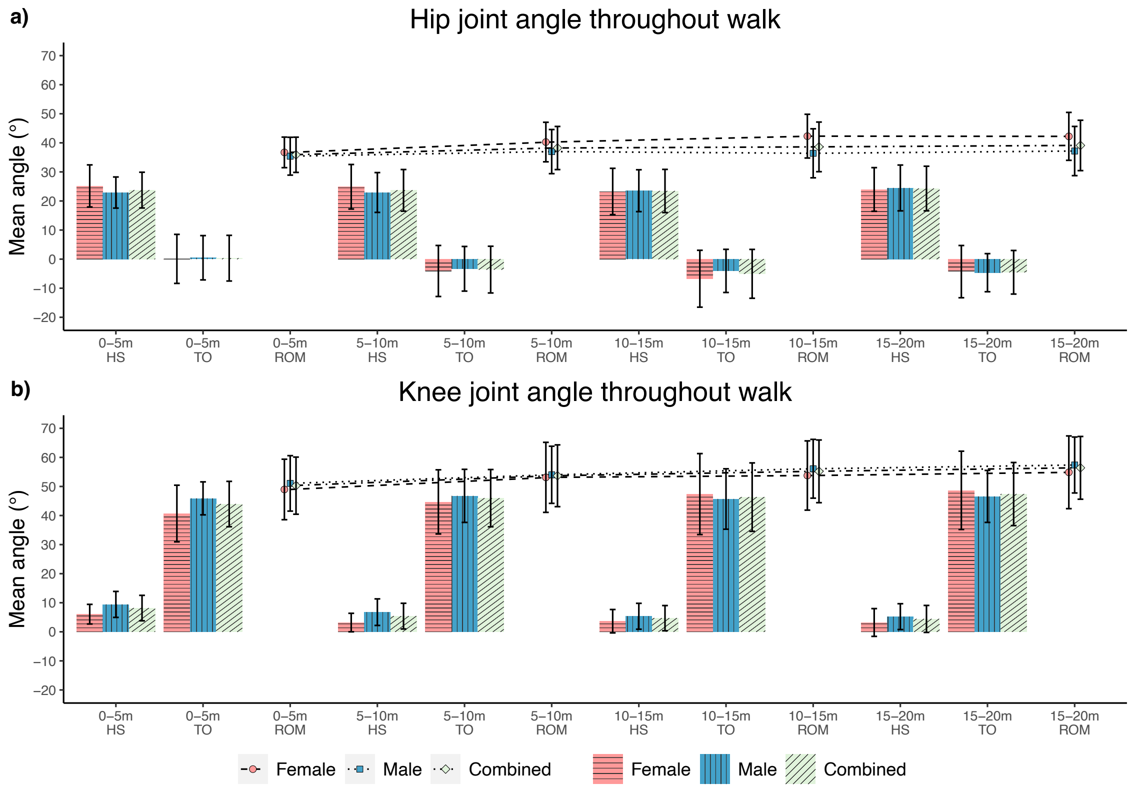


Figure 7.5 Joint ROM kinematic measures for each 5 m interval of the 20 m yoke walk, a) hip joint kinematics; b) knee joint kinematics.

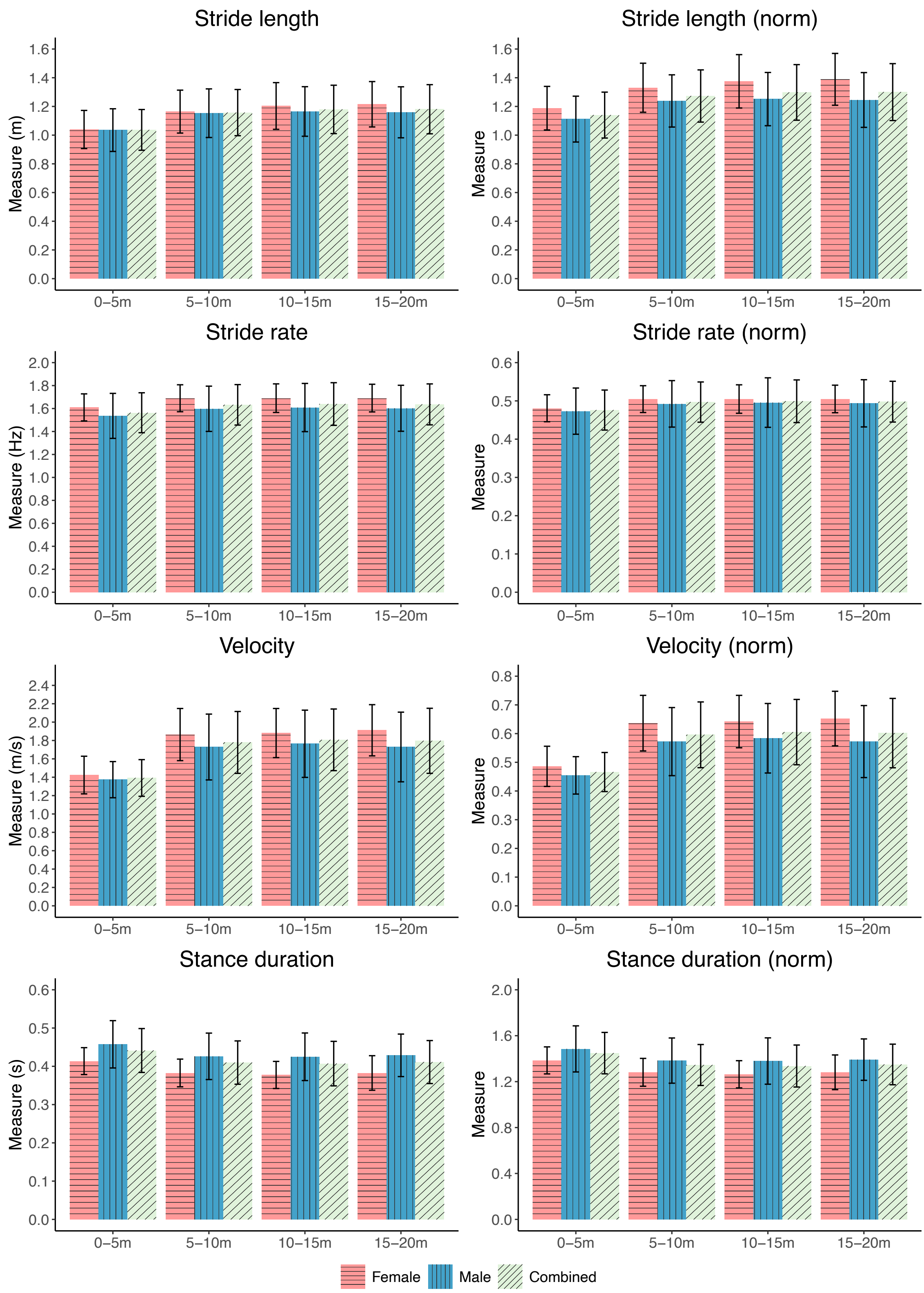


Figure 7.6 Spatiotemporal measures for each 5 m interval of the 20 m yoke walk.

## 7.6 DISCUSSION

The aim of conducting this study was to use ecologically realistic training loads and carry distances to: 1) establish the preliminary biomechanical characteristics of the yoke walk; 2) identify any biomechanical differences between male and female athletes performing the yoke walk; and 3) determine spatiotemporal and kinematic differences between stages (intervals) of the yoke walk. The research provides an initial description of the observed spatiotemporal and kinematic characteristics of experienced strongman athletes carrying loads similar to those seen in competition.

### 7.6.1 GENERAL BIOMECHANICAL CHARACTERISATION – SEX INDEPENDENT

Throughout the gait cycle of the yolk walk, athletes presented flexion of the hip and slight to neutral flexion of the knee at heel strike, slight to neutral extension of the hip and flexion of the knee at toe-off and moderate hip and knee ROM. When compared with the previously studied farmers walk, athletes exhibited reduced flexion of the knee at heel strike (farmers walk: 25.0 ± 7.3°; yoke walk: 5.7 ± 4.7°) and toe-off (farmers walk: 54.4 ± 8.7°; yoke walk: 45.9 ± 10.2°), and greater knee ROM (farmers walk: 29.0 ± 11.6°; yoke walk 53.9 ± 10.7°) during the yoke walk [30]. Shorter stride length (farmers walk: 1.54 ± 0.13 m; yoke walk: 1.14 ± 0.17 m), lower stride rate (farmers walk: 1.89 ± 0.13 Hz; yoke walk: 1.62 ± 0.18 Hz) and increased stance duration (farmers walk: 0.32 ± 0.04 s; yoke walk: 0.42 ± 0.06 s) were also reported for the yoke walk when compared with the farmers walk [30], with such differences likely due to the higher loads used in the yoke walk (yoke walk: 198.2 ± 54.8 kg; farmers walk: 181 ± 0.0 kg).

As described by Hindle, et al. [217], a physical limit exists where the load carried becomes so great that the athlete is not able to continue to increase or maintain their stride rate to compensate for the decrease in stride length, and thus a decrease in velocity occurs. The lower stride rate and stride length reported for the yoke walk when compared with the farmers walk [30] further highlights the inability of the athlete to continue to increase their stride rate to compensate for the loss of stride length under heavier loading. Identifying the threshold load or %1RM where stride rate begins to decrease may be of interest to strongman coaches and strength and conditioning coaches using loaded walks to target foot speed, core stability and total body strength adaptations [7].

Data from the current study indicates that from heel strike until the end of the double support phase, the knee is in a mostly extended state. The combination of an extended knee throughout the stance phase and a short stride length reduces the vertical displacement of the athlete's centre of mass (COM) [237], reducing the chance of "catching" the yoke on the ground. Where a reduced stride length requires an increase in stride rate to achieve an equivalent velocity, an increase in metabolic demand is expected [238, 239]. The increase in metabolic demand may however, be overcome by the reduced energy expenditure caused by; the reduced moments around the knee (as a result of reduced knee flexion during stance) [240], and the reduced requirement to lift the total system load against gravity (as a result of the reduced vertical COM displacement). When compared with the farmers walk, athletes performing the yoke walk exhibited both greater extension of the knee at heel strike and shorter stride lengths [30]. A reduced vertical COM displacement may be particularly important when performing the yoke walk due to the naturally smaller ground-to-implement clearance and greater total system load being carried when compared with the farmers walk. It is suggested that strongman athletes be careful in selecting an appropriate height of the yoke which simultaneously minimises the initial lift-off height and ensures the yoke does not catch during the walk. While the reduction in stride length supports hypothesis one, the increase in lower limb (knee) ROM and stance duration, and reduction in stride rate, as a result of the load threshold appearing to be crossed, is contrary to what was initially hypothesised.

### 7.6.2 General biomechanical characterisation – sex dependent

No differences were observed for the general biomechanical characteristics of the yoke walk between male and female athletes. Although conclusions of previous between-sex load carriage biomechanical studies are varied, the findings of the current study are in line with the lack of between-sex sagittal plane kinematic and spatiotemporal differences observed in previous literature using body-mass relative loading (≤ 30% body mass) [229] and relatively light absolute loads (i.e. 22 kg) [230]. The vastly different absolute loads and study populations in Silder, et al. [229] and Krupenevich, et al. [230] compared to the current study, should however, be acknowledged.

Several frontal and transverse plane between-sex kinematic differences have been observed in various athletic tasks such as walking, running and side-stepping [241-245]. It has been suggested that the greater number of between-sex differences observed in the frontal and transverse plane than the sagittal plane may be due to differences in muscle activation patterns [246, 247] and anthropometry [241] between sexes. The greater hip width to femur length ratio and quadriceps angle (Q-angle) typically observed in females, has been associated with greater knee valgus and external rotation of the knee during dynamic movements [248, 249]. Females have often typically been suggested to exhibit greater quadricep and reduced hamstring activity when compared to males [242, 250, 251], resulting in decreased resistance to anterior tibial shear stresses [252].

Note should be given to the absence of between-sex differences when men and women are matched for strength [231]. This absence leads to the suggestion that many of the observed between-sex differences in biomechanical research may be attributed to strength or skill instead of the actual sex of the athlete if relative strength is not considered [253]. Whilst keeping this in mind, further investigation into transverse and frontal plane kinematics and muscle activation patterns of male and female strongman athletes performing the yoke walk may assist in identifying any sex-specific injury risks associated with the yoke walk exercise.

The lack of spatiotemporal and sagittal plane kinematic between-sex differences observed in the current study supports hypothesis two.

### 7.6.3 Between-interval biomechanical differences – sex independent (main effect)

Athletes exhibited shorter stride length, increased stance duration, reduced stride rate and mean velocity, greater knee flexion at heel strike and hip flexion at toe off and reduced knee ROM during the initial interval (0 – 5 m) of the yoke walk when compared with the final three intervals (5 – 20 m). Such observations were consistent with differences between the initial and later intervals of a 20 m farmers walk [30]. The greater knee flexion at heel strike and hip flexion at toe off observed in the initial interval of the yoke walk likely contribute to the smaller knee ROM and stride length observed in the initial interval when compared with the later intervals. The abbreviated knee ROM may be a mechanism employed by athletes to rapidly increase stride rate during acceleration, before achieving maximal velocity through the optimisation of stride length (as a result of increased lower limb ROM) in the later intervals [254].

Although kinetic outcomes were not directly measured in the current study, the statistically greater change in velocity between interval one and interval two of the yoke walk when compared with all other immediately successive intervals, suggest a greater horizontal impulse applied by the athlete during the first interval (acceleration phase). This can be deduced in accordance with the impulse-momentum relationship and is supported by previous research on impulse differences between acceleration and maximal velocity phase sprinting [255].

Ballistic training may be of benefit to athletes when preparing for a yoke walk competition event in order to develop the neuromuscular capacities required to generate maximal force and thus greater propulsive impulse during relatively short periods of ground contact [256, 257]. Exercises such as the concentric-only half-squat (COHS) performed at 90% 1RM COHS with maximum ballistic intent is suggested to promote greater peak force production and relative impulse (intervals < 250ms) than lower loading (< 90%) performed with either maximum ballistic intent or sub-maximum ballistic intent [258]. Such training techniques may be used by strongman athletes and coaches to achieve greater performance in the yoke walk or other load carriage strongman events.

The observed differences in spatiotemporal and kinematic parameters between the initial acceleration (0 – 5 m) and later maximal velocity (5 -20 m) intervals are in support of hypothesis three of the study.

#### 7.6.4 BETWEEN-INTERVAL BIOMECHANICAL DIFFERENCES – SEX DEPENDENT (TWO-WAY INTERACTION)

Both male and female athletes exhibited shorter normalised stride length during the initial interval when compared with the final three intervals. Female athletes, however, also exhibited statistically shorter normalised stride length during the second interval than the final interval, indicating female athletes cover a greater distance before reaching maximal stride length than male athletes. Although female athletes in the current study had statistically shorter lower limb lengths than males, stride length was normalised to lower limb length, eliminating the effect of lower limb anthropometry on stride length. The observed difference, may however, be the result of males having a greater prevalence of type II fibres than females [259]. The greater prevalence of type II muscle fibres gives male athletes an advantage over female athletes during the acceleration phase where rapid force production is key to achieving maximal stride rate and stride length as quickly as possible.

Female athletes during the initial interval displayed greater extension of the knee at toe-off when compared with the final two intervals, and smaller hip ROM when compared with the final three intervals, whereas male athletes did not exhibit these characteristics. Similar to the suggested mechanism of reducing knee ROM to increase stride rate, as was observed for the group dataset, the greater extension of the knee at toe off and reduced hip ROM during the first interval when compared with the final intervals may have been a further mechanism employed by female athletes to increase stride rate and overcome the inertia of the load during the initial 5 m of the walk.

Where the main effects of sex on the biomechanics of athletes performing the yoke walk supported hypothesis two, in that, no between-sex differences were observed, the identified two-way interactions between sex and interval provide means to reject this hypothesis.

### 7.6.5 ADDITIONAL CONSIDERATIONS

The current study has a number of limitations which should be addressed. The MARG-based methodology used in the study has been reported to produce joint kinematic estimations which are highly representative of those estimated using an optical motion capture system for such functional fitness exercises as the squat (hip MAPE: 8.2 ± 6.5%; knee MAPE: 5.1 ± 3.7%), box squat (hip MAPE: 6.8 ± 6.1%; knee MAPE: 4.0 ± 2.7%) and sandbag pickup (hip MAPE: 7.0 ± 5.5%; knee MAPE: 3.7 ± 2.8%) [140]. This methodology, however, showed less agreement for knee (MAPE: 22.5 ± 16.5 %) and hip (MAPE: 25.1 ± 21.0 %) joint kinematics during a small ROM (hip: 14.3 ± 3.7º; knee: 22.9 ± 8.0º) shuffle gait pattern [140]. Although care should be taken when interpreting joint kinematic results in this study, greater validity may be expected for hip and knee joint kinematics of athletes performing the yoke walk than a shuffle walk gait pattern due to a reduced number of dynamic degrees of freedom caused by the increase in the complexity of the task (loading) [145, 260, 261] and the greater ROM observed during the yoke walk (hip: 37.9 ± 7.8º; knee: 53.9 ± 10.7º). Where ankle joint ROM in previous load carriage exercises have been reported to be small (Winwood, et al. [5]: 9.6 ± 9.8º; Keogh, et al. [30]: -3.0 ± 4.0º), the MARG-based methodology used was declared to be inappropriate for this application due to the expected small ROM of the ankle during the yoke walk, thus ankle joint measures were not included in this study.

The number of male (n = 12) and female (n = 7) athletes included in the current study are individually larger than the majority of previous strongman biomechanics studies [5, 29-32, 36, 70]. Nevertheless, the power analysis performed and relatively large between-sex effect sizes, large confidence intervals and corresponding statistical insignificance ($p > 0.05$) observed in some measurement parameters, indicates an under-powered sample size for between-sex comparisons [262]. Where possible, future studies should look to include a greater number of male and female athletes of similar competitive standard for between-sex analyses.

Another limitation of the current study may be the reliability of the 1RM pre-test protocol. Due to the wide range of ways in the yoke walk may be performed whereby competition organisers typically set various distance, loading and set formats (maximal distance in given time, specified distance in shortest time), the way in which researchers test an athlete's 1RM may introduce additional variability. Establishing a standardised testing protocol that ensures reliability in measuring an athlete's 1RM in the yoke walk across various competition formats may therefore be beneficial to future researchers.

As this is the first study in which kinematic and spatiotemporal parameters of the yoke walk have been measured, there is significant scope for future research, including: transverse and frontal plane kinematic analyses; establishing relationships between anthropometrics and biomechanical characteristics of athletes; the effect of yoke load on the biomechanics of an athlete; and the biomechanical determinants of greater performance in the yoke walk. Such research is expected to equip strongman athletes and coaches, and strength and conditioning coaches with the knowledge required to elicit greater performance when undertaking the yoke walk or similar heavy load carriage exercises whilst minimising the risk of injury to the athlete.

## 7.7 CONCLUSION

In conducting this study, the first descriptive data of the spatiotemporal and joint kinematic characteristics of male and female strongman athletes performing the yoke walk was established. A number of differences in spatiotemporal and kinematic measures were identified in the yoke walk when compared with previous load carriage research of the farmers walk and backpack load. Between-interval spatiotemporal and joint kinematic differences were observed between the initial (lower velocity/acceleration) and later (maximal velocity) intervals. No main between-sex differences and a limited number of two-way interactions between sex and interval were observed. It is suggested that an abbreviated lower limb ROM during the initial intervals will assist in rapidly increasing stride rate and therefore velocity. Further, the combination of a short stride length and high stride rate is suggested to minimise vertical yoke displacement and metabolic demand placed on the athlete while performing the yoke walk. The results of this biomechanical analysis of the yoke walk provides a preliminary description of the movement that will: assist strongman training and competition performance; improve strength and conditioning coaching practice for coaches interested in prescribing this exercise to non-strongman athletes; and establish significant scope for future research.

# CHAPTER 8:

# EXPERIMENTAL STUDY 2

# 8. THE BIOMECHANICAL CHARACTERISTICS OF THE STRONGMAN ATLAS STONE LIFT

## 8.1 PREFACE

The systematic reviews presented in Chapter 2 and Chapter 3 identified the lack of temporal and kinematic analyses of athletes performing the atlas stone lift as a major gap in the current field of strongman biomechanics research. Further, the only previous biomechanical analysis of the atlas stone lift, included three male strongman athletes performing a single repetition under lighter loading conditions than may be expected by strongman athletes of a similar body mass during training or competition. The study presented in this chapter describes the general movement pattern of experienced male and female strongman athletes performing the atlas stone lift using ecologically valid training loads and set formats. Part b) of Question 4, Question 5 and Question 6 were addressed in this chapter.

Supplementary tables (e.g., Table S1) referenced throughout this chapter can be found in Appendix 6.

This manuscript has been accepted for publication in PeerJ on 5 August 2021.

## 8.2 Abstract

**Background.** The atlas stone lift is a popular strongman exercise where athletes are required to pick up a large, spherical, concrete stone and pass it over a bar or place it on to a ledge. The aim of conducting this study was to use ecologically realistic training loads and set formats to: 1) establish the preliminary biomechanical characteristics of athletes performing the atlas stone lift; 2) identify any biomechanical differences between male and female athletes performing the atlas stone lift; and 3) determine temporal and kinematic differences between repetitions of a set of atlas stones of incremental mass.

**Methods.** Kinematic measures of hip, knee and ankle joint angle, and temporal measures of phase and repetition duration were collected whilst 20 experienced strongman athletes (female: n = 8; male: n = 12) performed three sets of four stone lifts of incremental mass (up to 85% one repetition maximum) over a fixed-height bar.

**Results.** The atlas stone lift was categorised in to five phases: the recovery, initial grip, first pull, lap and second pull phase. The atlas stone lift could be biomechanically characterised by: maximal hip and moderate knee flexion and ankle dorsiflexion at the beginning of the first pull; moderate hip and knee flexion and moderate ankle plantarflexion at the beginning of the lap phase; moderate hip and maximal knee flexion and ankle dorsiflexion at the beginning of the second pull phase; and maximal hip, knee extension and ankle plantarflexion at lift completion. When compared with male athletes, female athletes most notably exhibited: greater hip flexion at the beginning of the first pull (male: 63.7 ± 15.8º; female: 84.7 ± 18.7º; $d = -1.21$; $p < 0.001$), lap (male: 18.3 ± 16.0º; female: 31.5 ± 18.1º; $d = -0.77$; $p < 0.001$) and second pull (male: 37.4 ± 21.7º; female: 44.0 ± 23.2º; $d = -0.29$, $p = 0.034$) phase and at lift completion (male: 1.2 ± 10.3º; female: 12.5 ± 15.6º; $d = -0.85$, $p < 0.001$); and a shorter second pull phase duration (male: 1.653 ± 0.561 s; female: 1.428 ± 0.506 s; $d = 0.42$; $p = 0.012$). Independent of sex, first pull and lap phase hip and ankle range of motion (ROM) were generally smaller in repetition one than the final three repetitions ($-0.717 \leq d \leq -0.496$, $p \leq 0.002$), while phase and total repetition duration increased throughout the set ($0.64 \leq d \leq 1.73$, $p \leq 0.003$). Two-way interactions between sex and repetition were identified. Male athletes displayed smaller hip ROM during the second pull phase of the first three repetitions when compared with the final repetition and smaller hip extension at lift completion during the

first two repetitions when compared with the final two repetitions. Female athletes did not display these between-repetition differences.

**Conclusions.** Some of the between-sex biomechanical differences observed were suggested to be the result of between-sex anthropometric differences. Between-repetition biomechanical differences observed may be attributed to the increase in stone mass and acute fatigue. The biomechanical characteristics of the atlas stone lift shared similarities with the previously researched Romanian deadlift and front squat. Strongman athletes, coaches and strength and conditioning coaches are recommended to take advantage of these similarities to achieve greater training adaptations and thus performance in the atlas stone lift and its similar movements.

## 8.3 INTRODUCTION

Strongman is a competitive strength-based sport where athletes perform heavy, awkward and more physically demanding variations of common activities of daily living or traditional tests of strength. Strongman exercises are often derived from traditional weight training exercises such as the clean and press, deadlift and squat [51]. In a typical strongman competition event, an athlete may be required to lift large stones to various height ledges, carry weight-loaded frames, press large logs or dumbbells over-head or pull multi-ton vehicles such as trucks, buses or planes [13].

The atlas stone lift is a common strongman competition event which requires the athlete to pick up and place a large, spherical, concrete stone onto a ledge or over a bar (Figure 8.1). The diameter of the stone, mass of the stone and height of the ledge/bar can vary between competitions and between competition classes, which are typically based on sex and bodyweight. Common measures of performance in a competition atlas stone event is a maximum number of repetitions of a single mass stone over a bar in a timed period (usually 60 seconds), or the fastest time to place a series of stones (usually three to six stones) of incremental mass onto a ledge or over a bar.

Qualitatively, the atlas stone lift has been suggested to share biomechanical similarity to various traditional weight training exercises [217]. The initial lift of the stone off the ground may be similar to lifting a sandbag or medicine ball off the ground using a Romanian deadlift technique; lifting the stone from the lapped position may be similar to the initiation of the concentric phase of a box squat from the seated position; and the final drive from a quarter-squat position to passing the stone over a bar/onto a ledge may be similar to the concentric phase of a barbell front squat where the load is positioned on the anterior surface of the body [217].

Quantitative research into the biomechanics of athletes performing the atlas stone lift is limited, with the only study on this lift conducted to date analysing trunk muscle activation patterns and lumbar spine motion, load and stiffness [36]. Three experienced male strongman athletes (body mass: 117.3 ± 27.5 kg) performed a single lift of a 110 kg stone to a height of 1.07 m. When compared with other strongman lifts examined in the study, including the farmers walk, log lift, tire flip and yoke walk, the atlas stone lift was reported to result in the lowest lumbar spinal compression, which was suggested to be due to the athlete's ability to curve their spine around the stone and keep the centre of mass of the stone close to their lower back [36]. The findings of McGill and colleagues were not, however, consistent with the retrospective injury study by Winwood, et al. [14]. In a survey of 213 male strongman athletes, the atlas stone lift was reported to account for the greatest percentage of injuries caused by common strongman exercises (including the yoke walk, farmers walk, log lift and tire flip) with the bicep and lower back being the most common sites of atlas stone lift injuries [14]. The potential discrepancy in the findings of McGill, et al. [36] and Winwood, et al. [14] may be due to the relatively light loads and low height to which the stone was lifted by athletes in the study by McGill, et al. [36], when compared with what would be lifted by athletes of similar body mass in training and competition today (load: >180 kg; height: 1m to > 1.3 m).


Figure 8.1 An athlete performing the atlas stone lift. Image reproduced with permission from respective copyright owner and person pictured.

Between-repetition comparisons of heavy, awkward lifting exercises performed in immediate succession (no rest period between repetitions), such as a series of atlas stone lifts are limited. Changes in biomechanics between repetitions have been observed due to an increase in load when performing the barbell back squat, whereby as load approaches an athlete's one repetition maximum (1RM), greater trunk inclination and hip range of motion (ROM) has been observed [263]. The rest allocated between incremental load repetitions (loads of 80%, 90%, 100% 1RM; 5 min rest between each load) in Yavuz, et al. [263], should be noted as a distinct difference to a set of atlas stone lifts of incremental mass where minimal between-repetition rest periods typically occur during training and competition. Due to the differences in rest period and thus greater accumulation of acute fatigue in a series of atlas stone lifts when compared with squats performed in Yavuz, et al. [263], the transferability of the observations in Yavuz, et al. [263] to the atlas stone lift are still somewhat uncertain. Trafimow, et al. [264] demonstrated the effect of fatigue on the biomechanics of healthy male participants lifting loaded boxes (0 – 30 kg) from the floor to knuckle height. After performing an isometric half-squat hold (held until failure), participants employed more of a stoop lifting technique (straight leg) than a squat lifting technique (flexed knee), where the squat technique was preferentially used pre-fatigue. While qualitatively stoop and squat lifting techniques appear similar to components of the atlas stone lift, both the load (0 – 30 kg) and study population (healthy, recreationally active males) recruited in Trafimow, et al. [264] make it unclear whether such observations are transferable to the atlas stone lift performed by strongman athletes.

No studies have compared the biomechanics of male and female athletes performing the atlas stone or similar, heavy, awkward lifting exercises. A study by Lindbeck and Kjellberg [265] observed between-sex differences in lower limb and trunk kinematics of office workers performing a stoop and squat lifting technique. Men exhibited greater trunk ROM for both lifting techniques, while female athletes exhibited greater knee ROM in the squat lifting technique [265]. Similar to the box lifting study of Trafimow, et al. [264], the transferability of these observations to the atlas stone lift are uncertain due to the substantial difference in loading (male: 12.8 kg; female: 8.7 kg) and study populations (healthy office employees) compared to male and female strongman athletes performing the atlas stone lift. Of greater relevance to the atlas stone lift may be the studies of McKean and Burkett [266] and Lisman, et al. [267], where between-sex kinematic differences were observed in trained persons performing the back squat (50% body mass) and over-head squat (un-loaded), respectively. In these studies, female athletes displayed a more upright trunk position during the overhead squat [267] and back squat [266] than male athletes. Male athletes displayed greater peak hip flexion in the overhead squat than female athletes [267], while females displayed greater peak hip flexion in the back squat than male athletes [266].

As this study is the first of its kind, whereby spatiotemporal and kinematic estimates of male and female athletes performing the atlas stone lift are established, an emphasis is placed on the importance of undertaking a descriptive-type study of the movement pattern associated with the atlas stone lift. The aim of conducting this study was to use ecologically realistic training loads and set formats to: 1) establish the preliminary biomechanical characteristics of athletes performing the atlas stone lift; 2) identify any biomechanical differences between male and female athletes performing the atlas stone lift; and 3) determine temporal and kinematic differences between repetitions of a set of atlas stones of incremental mass. In alignment with the aim of the study it was hypothesised that: 1) various phases of the atlas stone lift will share biomechanical similarity with previously studied traditional weight training exercises; 2) differences in lower limb kinematics will be observed between male and female athletes, particularly at the hip joint; and 3) athlete biomechanics will change throughout the set, with greatest differences observed between the first and last repetition of the set.

By addressing this aim, researchers, strongman coaches and strength and conditioning coaches will be better equipped with the knowledge of the atlas stone lift biomechanics required to: provide strongman athletes with recommendation on how to perform the atlas stone lift based on the techniques of experienced strongman athletes; better prescribe strongman athletes with biomechanically similar exercises to the atlas stone lift for targeted training of specific phases of the lift; better prescribe the use of the atlas stone as a training tool for non-strongman athletes; and better structure future research into the strongman atlas stone lift.

## 8.4 MATERIALS & METHODS

### 8.4.1 EXPERIMENTAL APPROACH

A cross-sectional observational experimental design was used to describe the biomechanical characteristics of athletes performing the atlas stone lift and assess temporal and kinematic measures of an incremental mass, four atlas stone series. Well trained strongman athletes with strongman competition experience (Table 8.1) undertook two testing sessions. Session one consisted of a 1RM atlas stone lift to establish loading conditions for session two. Session two consisted of the collection of temporal and kinematic measures during three sets of four lifts of atlas stones of incremental mass (up to ~85% 1RM) over a fixed-height bar. Body mass, trochanterion-tibiale laterale height and tibiale laterale height anthropometric measures were taken by a trained person using ISAK methodologies [232] to assist in describing the study population.

### 8.4.2 PARTICIPANTS

Twenty experienced strongman competitors (12 male and 8 female) were recruited from two local strongman gyms (Table 8.1). All participants were required to have a minimum of 18 months' strongman training experience, have competed in a minimum of one strongman competition and be free from moderate or major injury for at least one week prior to testing. A moderate injury was defined as an injury that had stopped the athlete from performing a particular strongman exercise during a strongman session, while a major injury was defined as an injury which prevented the athlete from continuing with all exercises and/or the session completely [13, 14]. Participants meeting the above criteria were informed of the purpose of the study and asked to sign an informed consent form. Ethical approval was granted for all procedures used throughout this study by Bond University's Human Research Ethics Committee (BH00045).

Table 8.1 Participant characteristics.

| Descriptor | Female | Male |
|---|---|---|
| Age (years) | 31.8 ± 6.5 | 31.8 ± 7.8 |
| Body mass (kg) | 76.2 ± 15.4 | 115.6 ± 26.3 |
| Stature (m) | 1.653 ± 0.43 | 1.811 ± 0.086 |
| Femur length (m) | 0.399 ± 0.027 | 0.412 ± 0.045 |
| Tibia length (m) | 0.470 ± 0.022 | 0.519 ± 0.031 |
| 1RM atlas stone lift (kg) | 80.3 ± 12.0 | 141.3 ± 24.9 |
| Strongman training experience (years) | 2.1 ± 0.7 | 3.0 ± 1.7 |
| Strongman competition experience (number of competitions in past 2 years) | 4.1 ± 2.8 | 3.5 ± 2.2 |

### 8.4.3 Trial conditions

To achieve optimal performance during the session, athletes were asked to prepare for each session in the same way in which they would prepare for a regular training session. Due to the range of individual loading parameters and experience level of all athletes recruited in the study, self-directed warm up routines were performed by each athlete [5, 31, 32, 69, 233]. Warm up routines lasted ~15 – 30 minutes and included repetitions of the atlas stone lift at loads approaching those expected to be used by the individual throughout the session. Generally, athletes would begin their warm up with dynamic stretching, including resistance band exercises, followed by barbell-only (no additional load) squats or deadlifts. Athletes would move on to stone pickups (either performing a Romanian deadlift-like pickup of the stone from the ground, or lifting the stone in a full range of motion to bar height without passing the stone over the bar) at low loading (~ <60% 1RM). As athletes approached stone masses expected to be used in the session, the athlete would begin to complete full stone lift repetitions where the stone was passed over the bar. Athletes were permitted to use knee and elbow sleeves, lifting belts, arm/wrist wraps and tacky during sessions, as this is standard equipment used in competition and training.

### 8.4.4 Session protocols

Session one 1RM testing required athletes to lift a stone of greatest mass over a bar of fixed height (female: 1.2 m; male: 1.3 m). Athletes worked up to their heaviest stone in mass increments selected by the athlete. Mass increments were dependent on the mass of the stones available, the perceived effort of the previous lift and current training loads used by each participant. When an athlete failed to lift the stone over the prescribed height bar, the athlete was given one additional attempt to successfully complete the lift. Athletes were assigned rest periods of six to eight minutes between each stone attempt [55]. The mass of the heaviest stone the athlete was able to successfully pass over the bar was determined to be their 1RM.

Session two was performed a minimum of seven days after session one and required athletes to perform three sets of a four stone series over a bar (female: 1.2 m; male: 1.3 m) as quickly as possible. Each stone within the series were of incremental mass, where stone one (repetition one) ≈ 60% 1RM, stone two (repetition two) ≈ 70% 1RM, stone three (repetition three) ≈ 80% 1RM and stone four (repetition four) ≈ 85% 1RM (Table 8.2). As is the nature of the atlas stone, stones were of a fixed mass (mass could not be added or removed from the stone), therefore stones within each series were selected based on the closest stone mass available to fit the required percentage of 1RM for each participant. The diameter and surface finish of stone varied with the mass of the stone (Table 8.2).

To begin each set, the athletes were positioned in the typical atlas stone competition starting position with the stone on the ground between their legs and their hands resting on the bar for which the stone was to be passed over. On the signal "athlete ready, three, two, one, lift" the participant commenced lifting stone one over the bar. After the completion of each repetition, the next stone in the series was positioned in front of the participant by a trained loading assistant. When an athlete was unable to pass a stone over the bar or the final stone in the series was successfully passed over the bar the trial was concluded, with each series typically completed in 60 seconds.

Table 8.2 Stone series characteristics.

| Descriptor | Female | Male |
|---|---|---|
| Stone one (repetition one) | | |
| Mass (kg) | 50.1 ± 7.3 | 90.7 ± 18.8 |
| % 1RM | 62.6 ± 1.6 | 63.8 ± 4.3 |
| Diameter (m) | 0.354 ± 0.015 | 0.428 ± 0.027 |
| Stone two (repetition two) | | |
| Mass (kg) | 55.8 ± 7.6 | 100.6 ± 20.0 |
| % 1RM | 69.7 ± 2.0 | 70.9 ± 3.9 |
| Diameter (m) | 0.369 ± 0.012 | 0.441 ± 0.034 |
| Stone three (repetition three) | | |
| Mass (kg) | 61.9 ± 8.5 | 110.7 ± 19.3 |
| % 1RM | 77.3 ± 2.0 | 78.3 ± 4.3 |
| Diameter (m) | 0.377 ± 0.020 | 0.455 ± 0.029 |
| Stone four (repetition four) | | |
| Mass (kg) | 69.0 ± 11.6 | 120.5 ± 21.9 |
| % 1RM | 85.9 ± 3.0 | 85.2 ± 2.5 |
| Diameter (m) | 0.394 ± 0.029 | 0.471 ± 0.036 |

### 8.4.5 Data acquisition and analysis

Methodologies of Hindle, et al. [140] were used to estimate joint kinematics of athletes performing the atlas stone lift. Four magnetic, angular rate and gravity (MARG) devices (ImeasureU, Vicon Motion Systems Ltd., Oxford, UK) were used to capture acceleration, angular velocity (1125 Hz) and magnetic field strength data (112 Hz). MARG devices were positioned on the pelvis (halfway between the left and right posterior superior iliac spine), right thigh (approximately 150 mm proximal to the lateral epicondyle of the femur), right shank (approximately 100 mm distal to the lateral tibial condyle) and right foot (midway between the base of the foot and the lateral malleoli) [140]. The MARG data collected for each segment were input into a custom Matlab script (The Mathworks Inc., Natick, MA, USA) to measure hip, knee and ankle joint angles in the sagittal plane [140]. The methodology has shown acceptable to excellent agreement with optical motion capture methodologies in similar movements such as the squat, box squat and sandbag pickup [140].

Two video cameras (iPad Air 2, iOS 13.3.1, Apple Inc., CA, USA) were used to capture video data at 30 Hz (Figure 8.2). Video data were synchronised with MARG data using the ground impact of a submaximal jump performed immediately prior to the commencement of each set. The video data allowed for the calculation of the temporal parameters (phase duration, repetition duration), while joint kinematics at various instances throughout a repetition were obtained from the time-synched MARG data. Temporal and kinematic measurements assessed during each repetition of the atlas stone lift are defined in Table 8.3, with a pictorial representation of each phase of the lift presented in Figure 8.3.

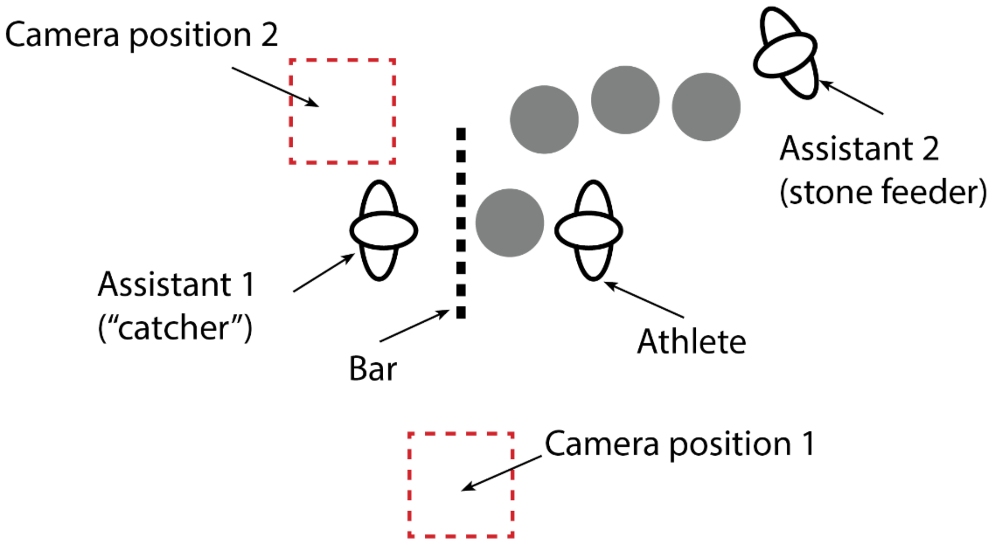


Figure 8.2 Schematic of equipment setup.

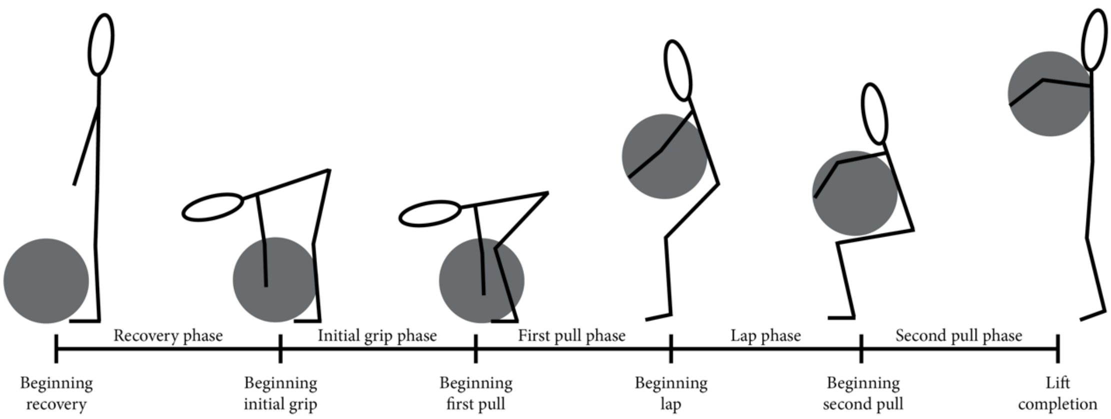


Figure 8.3 Atlas stone lift phase definition representation.

Table 8.3 Temporal and kinematic measurement definitions.

| Parameter | Definition |
|---|---|
| Recovery phase | Beginning: Stone set in front of the athlete (on 'lift' call for first repetition in set or once stone is placed in front of the athlete and the loader is clear in subsequent repetitions).<br>End: Instance/final instance* of the athlete first touching the southern hemisphere of the stone. |
| Initial grip phase | Beginning: Instance/final instance* of the athlete first touching the southern hemisphere of the stone.<br>End: Instance/final instance* of the stone leaving the ground. |
| First pull phase | Beginning: Instance/final instance* of the stone leaving the ground.<br>End: Stone reaching peak positive trajectory prior to a negative trajectory toward the lap of the athlete. |
| Lap phase | Beginning: Stone reaching peak positive trajectory prior to a negative trajectory toward the lap of the athlete.<br>End: Instance/final instance* of initial vertical movement of the stone from the lap position. |
| Second pull phase | Beginning: Instance/final instance* of initial vertical movement of the stone from the lap position.<br>End: > 50% of the stone passed over the bar. |
| Joint angle | Hip, knee and ankle angle at the beginning and end of each phase. Joint angle definitions provided in Figure 8.4. Positive angles denote flexion, negative angles denote extension. |
| Hip ROM | Maximum angle between the pelvis and thigh minus minimum angle between the pelvis and thigh throughout a given phase. |
| Knee ROM | Maximum angle between the thigh and shank minus minimum angle between the thigh and shank throughout a given phase. |
| Ankle ROM | Maximum angle between the foot and shank minus minimum angle between the foot and shank throughout a given phase. |

* *(final instance where multiple attempts were made to lift the stone off the ground).*

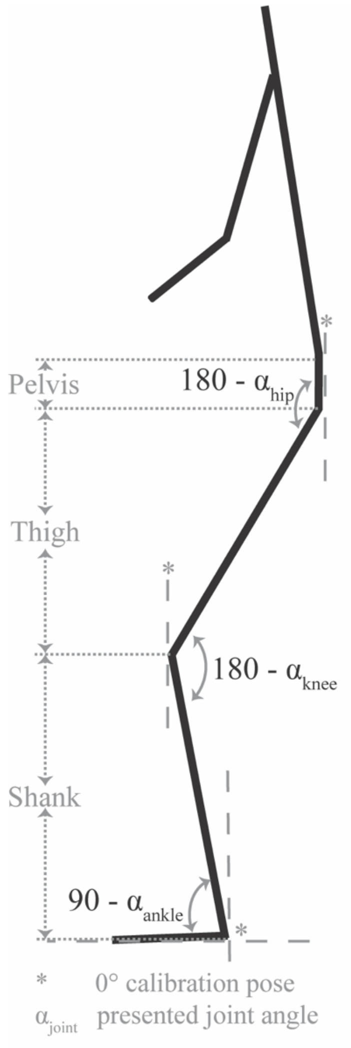


Figure 8.4 Joint angle definitions.

### 8.4.6 Statistical methods

Data were checked for normality using visual inspection and a Shapiro Wilks test. Homogeneity of variances were checked using Levene's test, homogeneity of covariances were checked using Box's M-test ($p < 0.001$) and sphericity was checked throughout the computation of ANOVA tests. Mean and standard deviations of all variables were calculated for all phases throughout the stone lift. The joint kinematic results for the recovery and initial grip phases were not presented due to the high variability in the participants' movements observed in these non-lifting, preparation phases, thus statistical analyses of these phases were not performed. A one-way repeated measures ANOVA test was used to establish the biomechanical characteristics of the lift by comparing: 1) between phase characteristics; 2) between repetition characteristics; and 3) between set characteristics. Between set statistical analysis was performed prior to further analyses to assess if data from each of the three sets could be combined. A two-way mixed model ANOVA test was used to identify interactions of sex and repetitions for each biomechanical characteristic. Partial eta-squared effect sizes ($\eta_p^2$) were calculated for two-way interactions with classifications of negligible ($\eta_p^2 \leq 0.01$), small ($0.01 > \eta_p^2 \geq 0.06$), medium ($0.06 > \eta_p^2 \geq 0.14$) and large ($\eta_p^2 > 0.14$) [236]. Bonferroni post-hoc pairwise t-tests were conducted on parameters where significant differences were detected. Cohen's d (d) effect sizes were calculated for t-tests with classification of negligible ($d < 0.2$), small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$) and large ($d \geq 0.8$) [236]. Post-hoc intra-class correlation coefficient (ICC) and standard error of measurement (SEM) metrics were calculated to assess relative and absolute reliability of each biomechanical measure, respectively. Reliability was classified as poor (ICC < 0.5), moderate (0.5 ≤ ICC < 0.75), good (0.75 ≤ ICC < 0.9) and excellent (ICC ≥ 0.9) [268]. Statistical analyses were performed in R version 3.6.1 (R Development Core Team, Vienna, Austria), with statistical significance accepted at $p < 0.05$ unless otherwise stated.

## 8.5 Results

A total of 216, 236 and 232 repetitions were analysed for the hip, knee and ankle, respectively. The failure to analyse all joints throughout some repetitions was attributed to sensor malfunction (hip = 16; ankle = 4), sensor detachment (hip = 4) and two participants failing to complete all four stone repetitions within the set (stone/repetition four failed attempts: n = 4). Sensor malfunction came in the form of sensors failing to commence data logging. Only full repetitions from successful lift off to lift completion were analysed.

### 8.5.1 General biomechanical characterisation – sex independent

The atlas stone lift could be characterised by: maximal hip and moderate knee flexion and ankle dorsiflexion at the beginning of the first pull and maximal hip ROM throughout the first pull; moderate hip and knee flexion and moderate ankle plantarflexion at the beginning of the lap phase and minimal hip, knee and ankle ROM throughout the lap phase; moderate hip and maximal knee flexion and ankle dorsiflexion at the beginning of the second pull phase and maximal knee and ankle ROM throughout the second pull phase; and maximal hip and knee extension and ankle plantarflexion at lift completion (Figure 8.5, Table S1, Table S2, Table S3).

Excluding the recovery and initial grip phases, the second pull phase was statistically longer in duration than all other lifting phases ($0.27 \leq d \leq 1.12$, $p < 0.001$), followed by the lap phase which was statistically longer in duration than the first pull phase ($d = 0.34$, $p < 0.001$) (Figure 8.5, Table S3).

### 8.5.2 General biomechanical characterisation – sex dependent

When compared with male athletes, female athletes exhibited: greater hip flexion ($d = 1.21$, $p < 0.001$) and ankle plantarflexion ($d = 0.78$, $p < 0.001$) at the beginning of the first pull and greater overall hip ROM throughout the first pull ($d = 0.56$, $p < 0.001$); greater hip flexion ($d = 0.77$, $p < 0.001$) and knee extension ($d = 0.58$, $p < 0.001$) at the beginning of the lap phase, and smaller hip ($d = -0.46$, $p = 0.001$) and ankle ROM ($d = -0.27$, $p = 0.049$) throughout the lap phase; greater hip flexion ($d = 0.29$, $p = 0.034$), knee extension ($d = 0.39$, $p = 0.004$) and ankle plantarflexion ($d = 0.48$, $p < 0.001$) at the beginning of the second pull phase, and smaller knee ROM ($d = -0.53$, $p < 0.001$) and greater ankle ROM ($d = 0.32$, $p = 0.021$) throughout the second pull phase; and greater hip flexion (d

= 0.85, p < 0.001) and ankle plantarflexion (d = 0.41, p = 0.003) at lift completion (Figure 8.5, Table S1, Table S4).

Few statistical between-sex temporal differences were observed (Table S5). Male athletes displayed a statistically longer second pull phase duration than female athletes (d = 0.42, p = 0.012) (Figure 8.5, Table S1, Table S4).

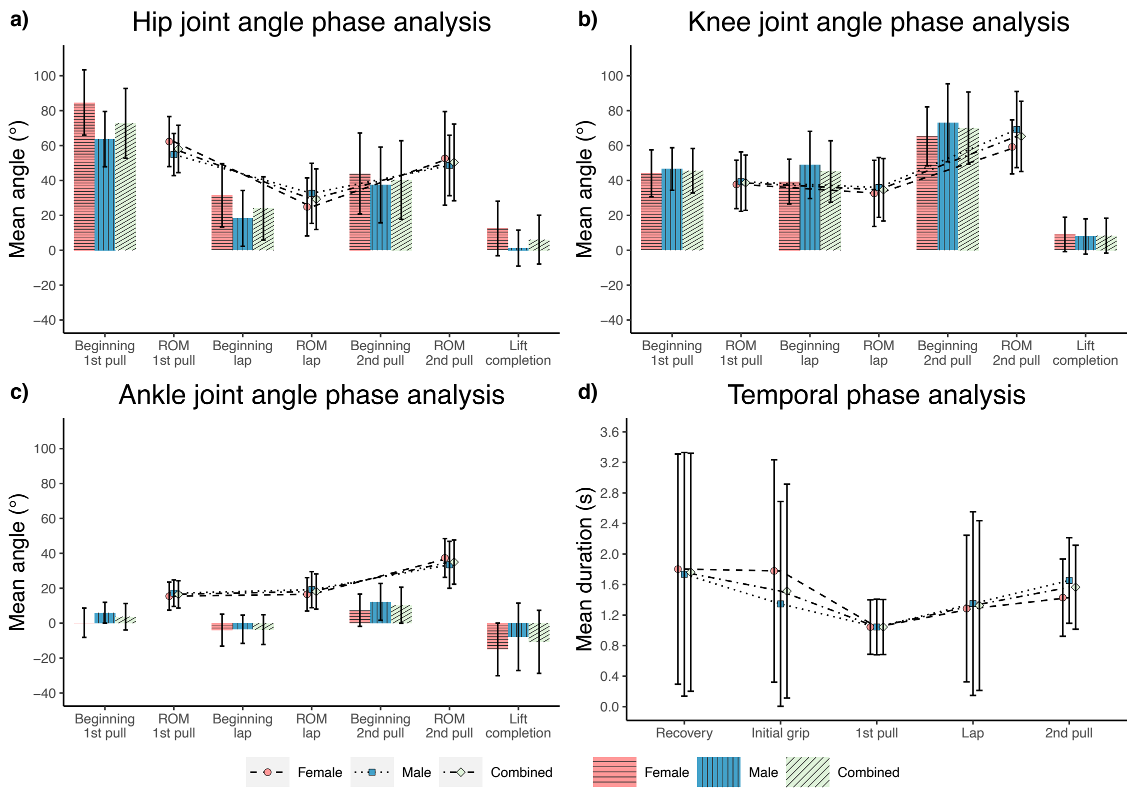


Figure 8.5 Repetition independent joint kinematic and temporal measures. a) hip joint kinematics; b) knee joint kinematics; c) ankle joint kinematics; d) temporal measures of each phase.

### 8.5.3 Between repetition biomechanical differences – sex independent (main effect)

Statistically significant between-repetition differences were most commonly observed for joint kinematics between combinations of the first two repetitions and the last two repetitions of the set (e.g., between repetition one-two and three-four) (Figure 8.6, Figure 8.7, Figure 8.8, Figure 8.9, Table S5). First pull phase hip and ankle ROM was smaller in repetition one than the final three repetitions (-0.72 ≤ d ≤ -0.50, p ≤ 0.002) (excluding repetition two ankle ROM). Lap phase hip and ankle ROM was smaller in repetition one than the final three repetitions (-1.15 ≤ d ≤ -0.46, p < 0.001), and smaller in repetitions two and three (hip only) than repetition four ($-0.65 \leq d \leq -0.37$, $p \leq 0.003$). No statistical between-repetition differences were observed at any joint for the position in which athletes began the second pull phase (Table S5).

For each repetition, individual phase durations and total repetition duration increased as the set progressed (Figure 8.10, Table S6), with medium to large effect sizes recorded between repetition one and repetitions three and four ($0.64 \leq d \leq 1.73$, $p \leq 0.003$). Where statistical differences were reported for phase duration between sequential stones (e.g., repetition one vs repetition two, repetition three vs repetition four), smaller effect sizes were typically observed ($0.31 \leq d \leq 1.03$, $p \leq 0.005$) (Table S6).

### 8.5.4 Between repetition biomechanical differences – sex dependent (two-way interaction)

While not evident in female athletes, male athletes generally displayed: smaller hip ROM during the second pull phase of the first three repetitions when compared with the final repetition ($-0.87 \leq d \leq -0.59$, $p \leq 0.011$); smaller hip extension at lift completion during the first two repetitions of the set when compared with the final two repetitions ($-1.24 \leq d \leq -0.55$, $p < 0.038$); and greater plantarflexion of the ankle at lift completion in the first repetition when compared with the final repetition ($d = 0.75$, $p = 0.014$) (Table S5, Table S6, Table S1). No temporal two-way interactions between sex and repetition were observed (Table S5).

### 8.5.5 Between set biomechanical differences

Between-set analysis was performed to identifying any potential effects of set number on the biomechanics of the athlete. Hip flexion was greater at the beginning of the first pull, lap phase and second pull in set one than set two and three ($0.04 \leq d \leq 0.26$, $p \leq 0.013$) (Table S7, Table S8, Table S9). Second pull duration was significantly greater during set one than set three ($d = 0.19$, $p = 0.012$) (Table S8, Table S9). No statistical between-set difference in total repetition duration was observed for any repetition.

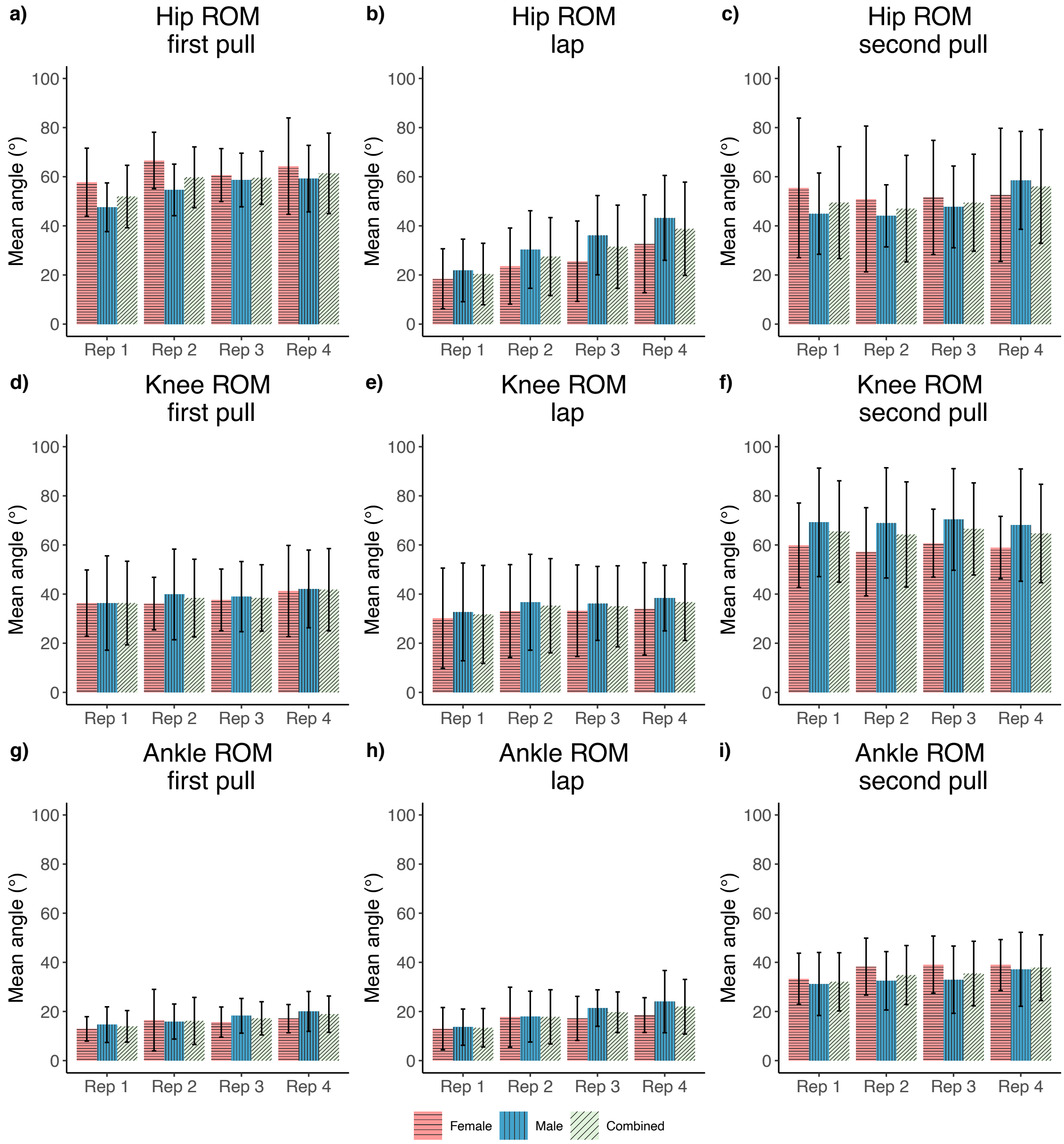


Figure 8.6 Sex and repetition dependent joint ROM kinematic measures for each phase, a-c) hip joint kinematics; d-f) knee joint kinematics; g-i) ankle joint kinematics.

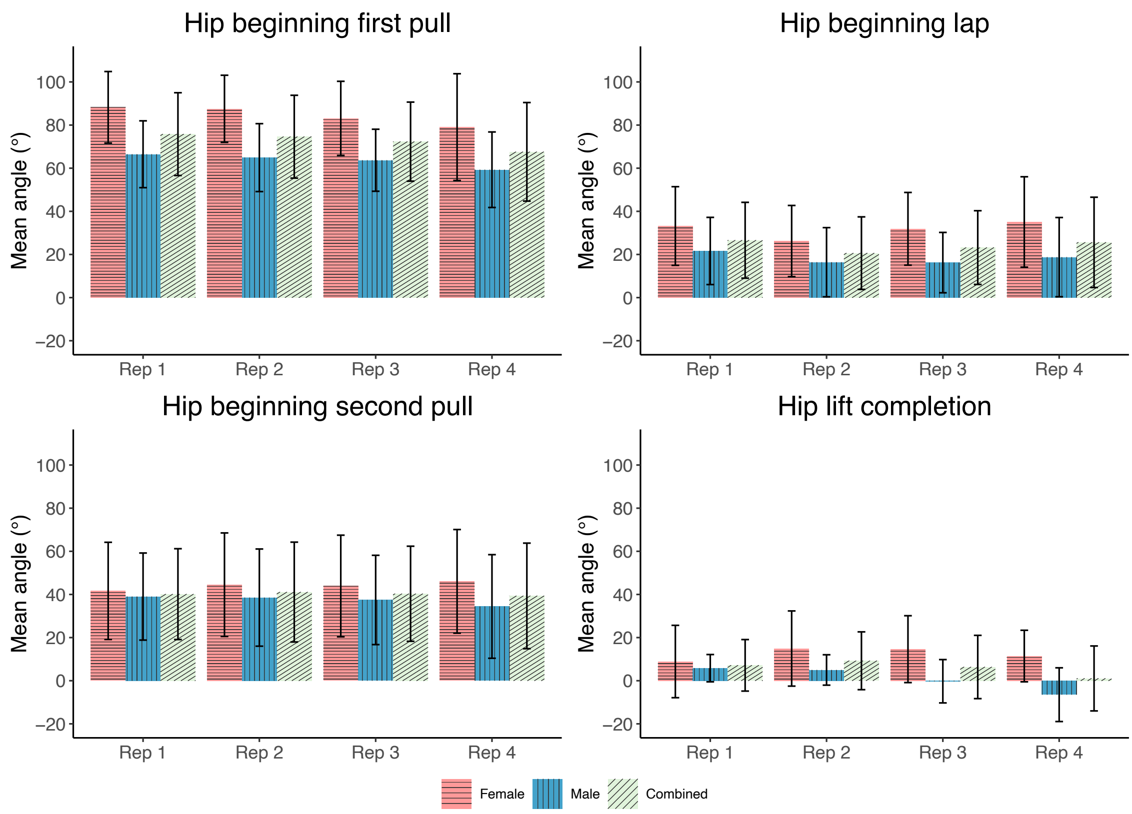


Figure 8.7 Sex and repetition dependent hip joint kinematic measures for beginning/end of each phase.

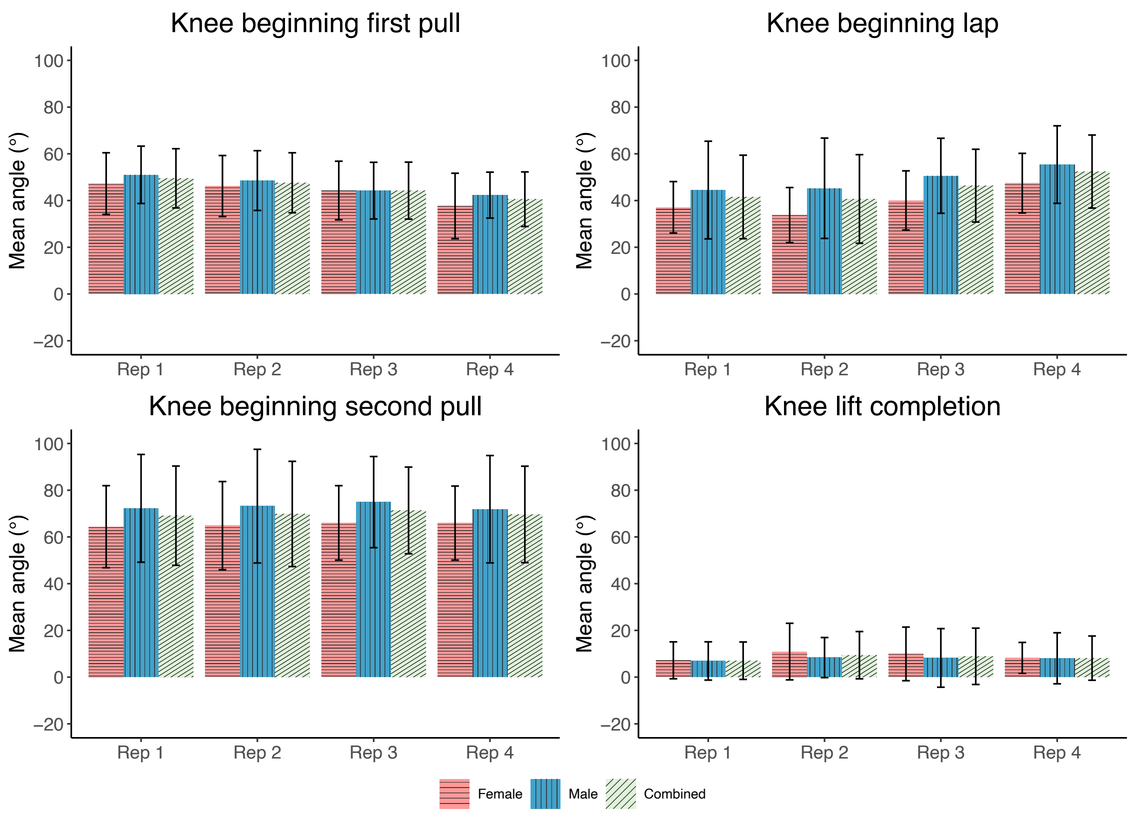


Figure 8.8 Sex and repetition dependent knee joint kinematic measures for beginning/end of each phase.

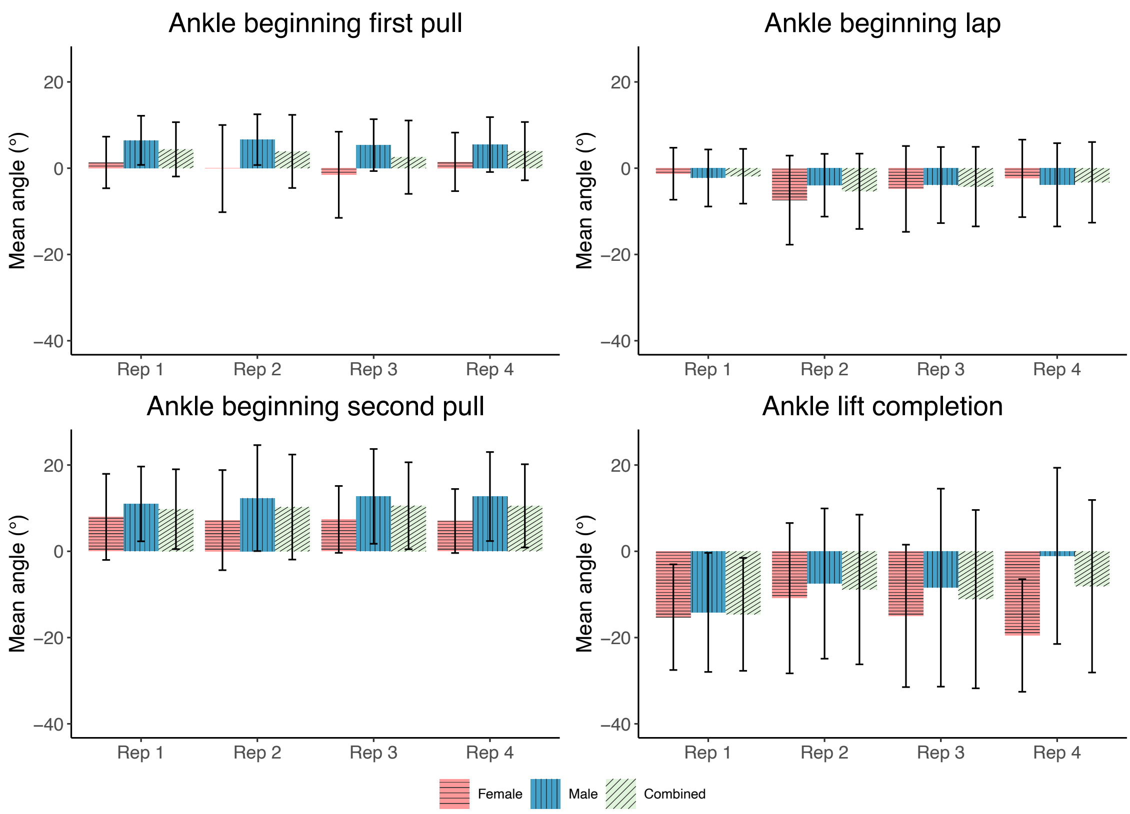


Figure 8.9 Sex and repetition dependent ankle joint kinematic measures for beginning/end of each phase.

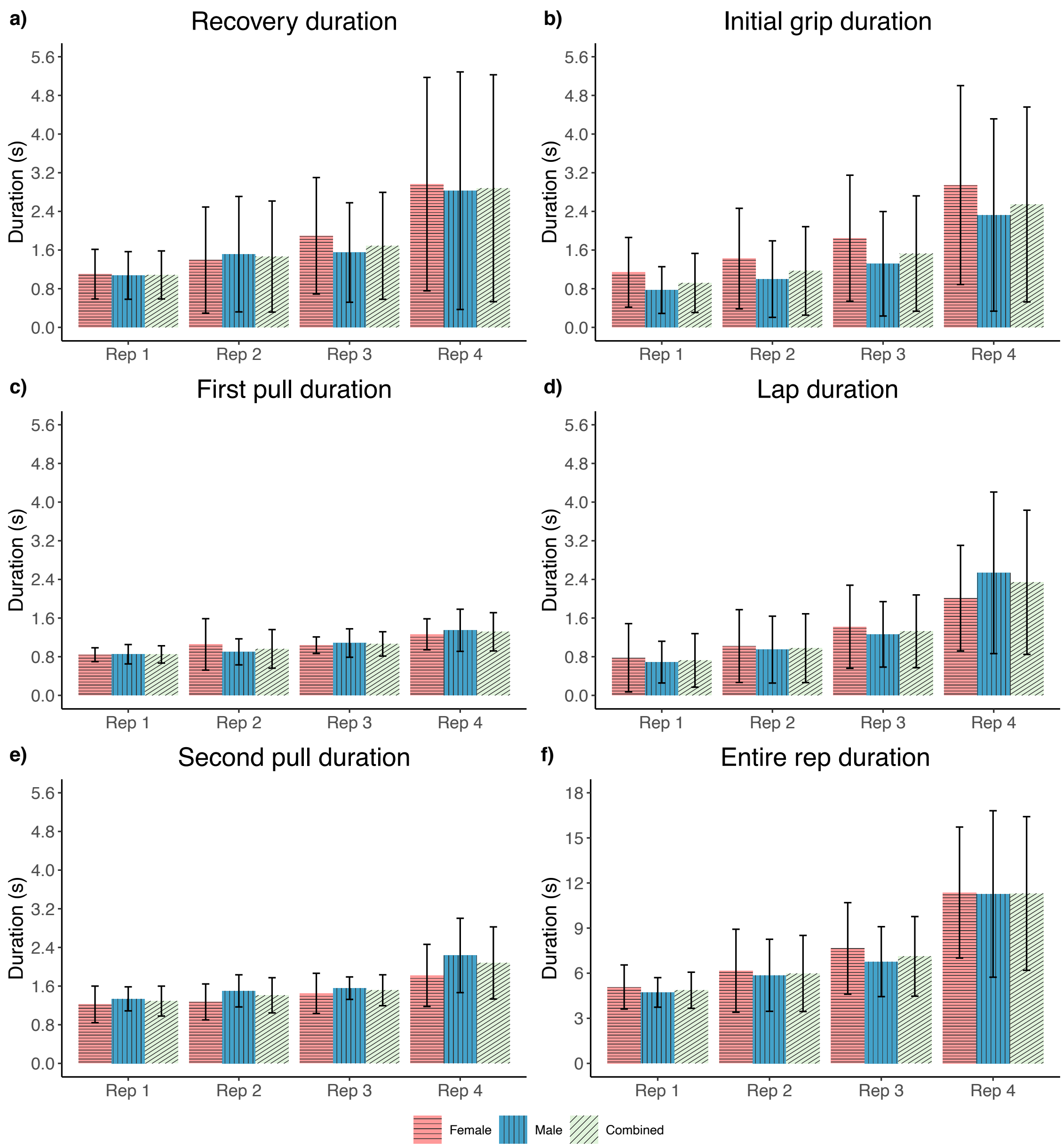


Figure 8.10 Sex and repetition dependent temporal measures, a) recovery phase; b) initial grip phase; c) first pull phase; d) lap phase; e) second pull phase; f) entire repetition.

## 8.6 Discussion

In alignment with the descriptive nature of the research, the aim of conducting this study was to use ecologically realistic training loads and set formats to: 1) establish the preliminary biomechanical characteristics of athletes performing the atlas stone lift; 2) identify any biomechanical differences between male and female athletes performing the atlas stone lift; and 3) determine temporal and kinematic differences between repetitions of a set of atlas stones of incremental mass.

### 8.6.1 General biomechanical characterisation – sex independent

To describe the general movement pattern of the atlas stone lift, testing hypothesis one sought to determine if the various phases of the atlas stone lift were biomechanically similar to selected traditional weight training exercises.

#### 8.6.1.1 *Recovery and initial grip phase*

Only temporal parameters were measured for the recovery and initial grip phase due to the high variability in joint kinematics observed during data collection and upon review of video data. This variability included athletes repositioning the stone by foot, and various individual set-up routines. The recovery and initial grip phases may be viewed as 'preparation' phases where the stone is yet to be physically lifted from the ground. These phases may be analogous to the athlete approaching the bar and first touching the bar in a 1RM deadlift, or the phase which may be defined between when an athlete returns the bar to the ground before lifting it back up in an as many repetitions as possible (AMRAP) deadlift event.

#### 8.6.1.2 *First pull phase*

The beginning of the first pull phase of the atlas stone lift was characterised by maximal hip flexion and moderate knee flexion and ankle dorsiflexion. The maximal hip flexion ($72.7 \pm 20.0^{\circ}$) at the beginning of the first pull phase was similar to that of the maximal hip flexion occurring during the Romanian deadlift ($79.97 \pm 15.85^{\circ}$) [269]. Knee flexion at the beginning of the first pull in the atlas stone lift ($45.6 \pm 12.7^{\circ}$) was however, slightly larger than the knee flexion reported for the Romanian deadlift ($33.86 \pm 12.59^{\circ}$) [269]. The relative similarity in the starting position of the atlas stone lift to the Romanian deadlift in conjunction with previous research on the trunk muscle activation patterns of athletes performing the atlas stone lift [36] and the Romanian deadlift [270], suggest that performing the first pull phase of the atlas stone lift may result in similar training adaptations to the Romanian deadlift. Schellenberg, et al. [271] reported similar maximal hip flexion (75.3 ± 9.2º) when athletes performed goodmornings with an external barbell load of 25% body mass. Where an athlete is required to focus on strengthening the hamstrings or is unable to perform either the atlas stone lift or Romanian deadlift due to specific injuries which prevent grasping a stone or barbell, goodmornings may be a suitable accessory exercise.

The first pull phase of the atlas stone lift was statistically shorter in duration than all other lifting phases (1.043 ± 0.360 s) and involved the largest ROM of the hip and second largest knee ROM of all phases. This indicates that a rapid extension of the hip and knee is key in initiating movement of the stone from the ground to a position close to the athlete's chest and centre of mass (COM) at the beginning of the lap phase. Training for power and rate of force development during rapid extension of the hip and knee and to a lesser extent the ankle may promote the physiological adaptations required for greater performance throughout the first pull phase of the atlas stone lift [55, 272].

Performing pulling derivatives of the snatch and clean and jerk, using strategic loading schemes is expected to assist in developing such power and rate of force development characteristics. Performed with moderate load, the power clean/snatch from the floor and clean/snatch pull from the floor is suggested to promote a component of the lift characterised by higher-velocity (when viewed on a force-velocity continuum), over a wide ROM [273]. While the mid-thigh pull, performed with moderate loading may assist in developing greater rate of force development, with the smaller ROM replicating the later portion of the first pull phase of the atlas stone lift [274].

#### 8.6.1.3 *LAP PHASE*

At the beginning of the lap phase, the athlete is generally in a position of moderate hip (24.0 ± 18.1º) and knee flexion (45.1 ± 17.6º), and moderate ankle plantarflexion (-3.7 ± 8.5º), supporting the lower portion of the stone with the hands and arms. For the majority of the athletes, gripping the stone with the hands on the lower portion of the stone throughout the entirety of the lift provided insufficient clearance to pass the stone over the bar upon standing with full extension of the hips and knees and an anatomical ankle position. To overcome this, athletes typically attempted to pull the stone as high as possible toward the chest at the end of the first pull/start of the lap phase, before retrieving and resting the stone in the lap. Whilst in the lap, the athlete re-gripped the stone with the arms and hands hugging the upper portion of the stone. The relatively large variance in the duration of the lap phase (1.325 ± 1.112 s) was representative of the time some athletes invest in ensuring a secure grip of the stone, whereby failing to grip the stone may result in dropping the stone during the second pull phase, costing the athlete time and energy in re-attempting the lift.

Two athletes used a "zero-lap" phase technique (commonly referred to as a "one-motion" technique within the strongman community) for the first two repetitions of each set, whereby the stone was lifted in a single motion with no transition of grip, no negative trajectory of the stone and thus, no lap phase. Employing the zero-lap technique likely reduces the total duration of the repetition. The two athletes that used this technique were the tallest athletes, indicating a possible advantage for taller athletes when lifting stones of lower mass (relative to 1RM) to/over an object of the same absolute height. It would appear to be less critical for taller athletes to attain a high stone position at the top of the chest (as demonstrated by the zero-lap phase technique) at the beginning of the lap phase, allowing for a fast transition through the phases of the lift until completion. The suspected advantage of taller athletes may, however, be lost or amplified depending on the competition rules (which determines the height of the bar/platform). The effect of athlete stature on their competition performance outcome may be a particular area of interest for future research.

A short ROM, double knee bend technique was used sporadically by some athletes to initiate a stretch shortening cycle just prior to the beginning of the second pull phase. While the stretch-shortening cycle is commonly used in weightlifting events to ensure maximal force and power can be rapidly applied to the barbell [31, 275, 276], evidence supporting its effectiveness for heavy/strength-based lifts performed over an extended duration, such as the atlas stone lift, is conflicting [79, 277].

#### 8.6.1.4 *Second pull phase*

Moderate hip (40.2 ± 22.5º) and maximal knee (70.0 ± 20.7º) flexion and ankle dorsiflexion (10.3 ± 10.3º) at the beginning of the second pull phase, and maximal knee (65.2 ± 20.1º) and ankle (35.0 ± 12.7º) ROM throughout the second pull phase were observed for the atlas stone lift.

The concentric movement of the stone throughout the second pull phase, with the load positioned in front, has been qualitatively suggested to share kinematic characteristics with the front squat [217]. The front squat has, however, been characterised by greater hip (94.2 ± 22.4º) and knee (125.1 ± 12.6º) flexion at the beginning of the concentric phase than the atlas stone lift [278]. Where greater strength adaptations may be achieved by performing an exercise with increased ROM [279], strongman coaches may consider using the front squat in the training programs of strongman athletes to target the general knee and hip extension requirements of the atlas stone lift through a greater ROM, thus encouraging greater strength adaptations.

The final instance of the second pull phase (lift completion) demonstrates the triple extension of the hip and knee and plantarflexion of the ankle to a position where the athlete is in an almost-neutral standing position (hip: 6.1 ± 14.0º; knee: 8.4 ± 10.0º; ankle: -10.7 ± 18.1º). Although only quantifiable in the current study by the variance in kinematic measures, this rapid triple extension appeared to visually vary within and between athletes. For example, some athletes were able to perform the triple extension with enough power and timing to project or 'pop' the stone off their chest and onto/over the bar. In the pop technique, the athlete qualitatively appeared to lift the stone at a normal rate from the beginning of the second pull phase, before quickly extending the hip and spine toward the end of the second pull phase. As a result of the rapid movement of the stone towards the end of the second pull phase, the stone appears to 'pop' off the athlete's chest and pass over the bar without the athlete remaining in contact with the stone. On the other hand, athletes who had to 'grind' the stone over the bar, displayed a substantial decrease in vertical stone velocity as the centre of mass of the stone approached the height of the bar. These athletes sometimes exhibited both hip extension and ankle plantarflexion as the stone passed over the bar. Athletes using the grind technique appeared to have to apply a force to the stone up until the precise moment at which the stone passed over the bar.

In alignment with hypothesis one, some biomechanical similarity was present between phases of the atlas stone lift and traditional weight training exercises including the Romanian deadlift and front squat.

### 8.6.2 General biomechanical characterisation – sex dependent

A number of between-sex differences in joint kinematics were observed. Most notably, female athletes exhibited greater hip flexion (female: 84.7 ± 18.7º; male: 63.7 ± 15.8º) and ankle plantarflexion (female: 0.3 ± 8.4º; male: 6.0 ± 6.0º) at the beginning of the first pull, lap and second pull phase than male athletes.

The between-sex difference in hip flexion at the beginning of the first pull may be the result of the differences in anthropometric ratios of the female and male population. At the beginning of the first pull, a greater arm to lower limb length ratio would enable an athlete to grip the bottom of the stone with less flexion of the hip (assuming constant knee flexion angle). Keogh, et al. [280] reported statistically greater arm to leg length ratios in male powerlifters (67.8 ± 2.9%, n = 54) when compared with female powerlifters (64.5 ± 2.5%, n = 14), supporting the deduction that the between-sex differences observed in hip flexion at lift off for the atlas stone lift may be partially due to the anthropometric differences between male and female strength athletes.

The smaller hip flexion displayed by male athletes at the beginning of the lap and second pull phase may be a mechanism used by male athletes to accommodate the larger diameter stone (typically lifted by male athletes when compared with female athletes) so to ensure the COM of the stone remains as close as possible to their COM and within their base of support. The compensative mechanism of greater hip extension may result in a similar stone to body COM distance and thus resistive moment arm length about the lumbar spine in male and female athletes. Although not measurable in the current study, such a result has been reported in a study in which males had significantly greater absolute but not relative L5/S1 joint moments than females when lifting boxes between 15 – 24 kg from a pallet at a self-selected pace [281]. The between-sex differences in hip, knee and ankle joint kinematics and phase duration measures observed while athletes performed the atlas stone lift are in support of hypothesis two.

### 8.6.3 Between repetition biomechanical differences – sex independent (main effect)

Hip and ankle joint ROM during the initial pull and lap phase of the lift were generally smaller for athletes during repetition one when compared with the final three repetitions. Greater flexion of the knee and hip at the beginning of the first pull were generally observed in the first two repetitions when compared with the final two repetitions.

The smaller hip and ankle ROM in the initial repetitions than the later repetitions indicate athletes performed abbreviated versions of the lift to begin the set. The strategy of athletes performing an abbreviated version of the lift is likely executed with the intention of self-preservation of energy [282] and conservation of overall repetition and set time. This is supported by the statistically shorter phase durations and total repetition duration observed during the first two repetitions when compared with the final two repetitions of the set. The increased hip ROM when lifting the greater mass stones is also in line with previous research on load-dependant biomechanical differences observed during the back squat [263].

Although fatigue was not directly measured in this research, the short recovery duration between each repetition may contribute to some level of athlete fatigue. Recovery phase duration was found to increase as athletes progressed through the set of four atlas stone lift repetitions. Where the onset of fatigue is observed, research has demonstrated significant changes in joint kinematics of male participants performing a box lifting task [264]. Such previous research may suggest that some of the between repetition differences observed in the current study be due to the acute effect of fatigue that progressively increased within the set of incremental mass stone lifts. In support of hypothesis three, a number of between-repetition differences were observed in athletes performing the atlas stone lift. Further, a large portion of between-repetition differences observed were between repetition one and four.

#### 8.6.4 Between repetition biomechanical differences – sex dependent (two-way interaction)

Male athletes exhibited smaller hip ROM during the second pull phase of the first three repetitions when compared with the final repetition and smaller hip extension at lift completion during the first two repetitions of the set when compared with the final two repetitions. Female athletes appeared to use a more consistent technique throughout the four repetitions, whereby they did not exhibit these significant between repetition differences.

To ensure the bottom of the stone cleared the height of the bar in the final two repetitions, male athletes appeared to use greater extension (often hyperextension) of the hip. The greater extension of the hip at lift completion, likely contributed to the greater hip ROM displayed by male athletes in the final repetition when compared to the first three repetitions.

While the two-way interactions between sex and repetition further support hypothesis three, the exact reasoning behind the different mechanisms used throughout the set by male and females is somewhat unclear. Future researchers may look to investigate how between-sex differences in anthropometry, motor control and muscle recruitment strategies contribute to the kinematic between-sex differences observed during the atlas stone lift series.

### 8.6.5 ADDITIONAL CONSIDERATIONS

The current study is not exempt from limitations. As with any research, care should be taken when interpreting comparative results between groups, ensuring the magnitude of the error of the measurement system is recognised. In the case of the temporal parameters, the measurement accuracy was limited by the frame rate of the video camera, while kinematic parameters were limited by the accuracy of the MARG-based motion capture methodology [140]. Good (ICC $\geq$ 0.75) to excellent (ICC $\geq$ 0.9) relative reliability was however, generally found for all biomechanical parameters measured within the study using the MARG and video camera methods (Table S10). When comparing results between studies, the technology used to capture data should be considered. This is particularly important when using relatively new technology or methods, such as MARG-based motion capture, as was used for this research.

Twenty experienced strongman athletes (12 male, 8 female) were recruited for the study. While the combined number of male and female strongman athletes recruited in the current study is much larger than the number of strongman athletes recruited in any previous strongman exercise biomechanics study, the individual number of male (n = 12) and female (n = 8) participants is similar or only slightly larger than previous research [5, 29-32, 36, 69, 70]. A greater number of both male and female athletes would strengthen the conclusions drawn from the observed between-sex biomechanical differences.

The absence of pre-test 1RM reliability metrics may be identified as a limitation of the current study. The way in which the atlas stone lift is performed varies at the discretion of competition organisers. Competition organisers may set various lift heights, loading schemes and set formats, whereby the set may be performed as a maximal single mass stone, maximal number of repetitions of a single stone in a timed period, or fastest time to complete a series of stones (as per the current study). Future researchers may look to establish standardised protocols to test an athletes 1RM across the various formats of the atlas stone lift.

Variation in the increments of the mass of the stones, dimensions of stones and surface finish of stones may also be viewed as a limitation to this study. Variable increments, dimensions and surfaces of stones, is however a reality of the sport of strongman and provides greater insight into the realities of strongman biomechanics.

As this is the first biomechanics study to describe kinematic and temporal parameters of athletes performing the atlas stone lift there is much scope for future research, including: transverse and frontal plane joint kinematic analyses; establishing relationships between anthropometrics of strongman athletes and their biomechanical characteristics; the effect of stone dimension, mass and surface finish on the biomechanics of an athlete; the injury risks associated with the atlas stone lift; and the biomechanical determinants of greater performance in the atlas stone competition event.

## 8.7 CONCLUSIONS

Conducting this study has resulted in the first kinematic and temporal description of male and female athletes performing the atlas stone lift using set and repetition schemes that are commonly used in strongman training. The atlas stone lift could be biomechanically characterised by a recovery, initial grip, first pull, lap and second pull phase. Between-sex biomechanical differences were suggested to be, in-part, due to anthropometric differences between sexes, while between-repetition differences may be attributed to increases in stone mass as well as some acute fatigue that increased throughout the set. Strongman athletes, coaches and strength and conditioning coaches are recommended to take advantage of the similarity shared between the atlas stone lift and traditional weight training exercises of the Romanian deadlift and front squat, and pulling derivatives of the snatch and clean and jerk to achieve greater performance in the atlas stone lift and its similar traditional weight training movements.

# CHAPTER 9:

# GENERAL DISCUSSION

# 9. DISCUSSION

The aim of the PhD thesis was to develop, validate and use ecologically valid motion capture methods to describe the biomechanics of experienced male and female strongman athletes undertaking previously under-assessed strongman exercises, to better inform the practices of strongman coaches and athletes and strength and conditioning coaches.

The overarching aim of this thesis was achieved by answering six guiding research questions.

1) What is already known about the biomechanics of athletes performing strongman exercises and where are the current gaps in the field of knowledge?

2) What data collection methods have been used in previous strongman biomechanics research?

3) How may current inertial motion capture methods be used and further developed to characterise the biomechanics of athletes performing strongman exercises?

4) What are the general biomechanical characteristics of the: a) yoke walk; and b) atlas stone lift?

5) What are the biomechanical differences between: a) different intervals of the yoke walk; and b) each repetition of a set of atlas stones of incremental mass?

6) Are there any biomechanical differences between male and female strongman athletes performing the: a) yoke walk; and b) atlas stone lift?

These six research questions were answered via two systematic reviews (Chapter 2 and Chapter 3), one technical summary review (Chapter 5), one methodological validation study (Chapter 6) and two cross-sectional analyses (Chapter 7 and Chapter 8). This chapter summarises the findings of these studies and explicitly outlines how each research question was answered.

Whilst this chapter attempts to avoid repetition of research questions and the outcomes achieved by answering the research questions, some repetition exists to provide a link between the results of each chapter, the research question(s) and the aim of the PhD thesis.

## 9.1 ALIGNMENT WITH CURRENT RESEARCH

The two systematic reviews and one technical summary provided scope for the research project and assisted in directing the design of the methodological validation study and two strongman biomechanics experimental studies to build on the current field of inertial motion capture (IMC) and strongman biomechanics research.

### 9.1.1 SYSTEMATIC REVIEW 1 AND SYSTEMATIC REVIEW 2

Systematic Review 1 answered Question 1 "*What is already known about the biomechanics of athletes performing strongman exercises and where are the current gaps in the field of knowledge?*", and Question 2 *"What data collection methods have been used in previous strongman biomechanics research?"*.

From Systematic Review 1, it was established that the biomechanics of eight strongman exercises had been analysed in previous literature. These exercises were the: atlas stone lift [36], farmers walk [5, 6, 30, 36, 71], heavy sled pull [29, 32], keg carry [36], log lift [6, 31, 36, 69], suitcase carry [36], tyre flip [6, 36, 70] and yoke walk [36]. Biomechanical characteristics of the these strongman exercises were established across ten studies with muscle activity [36, 71], spatiotemporal [5, 29, 30, 32, 69, 70], kinematic [5, 29-32, 69], kinetic [5, 31, 32, 36, 69] and anthropometric [6] analyses performed.

Previous research into the biomechanics of strongman exercises has been limited to males with similar body composition but highly varied training backgrounds, ranging from rugby and strength-trained athletes to strongman athletes. Loads lifted by athletes were either a constant absolute load for all athletes or based on a percentage the individual athlete's one or six repetition maximum of a particular exercise.

Two-dimensional (2D) video motion capture (VMC) was the most common method for the measurement of spatiotemporal and joint kinematic parameters [5, 29-32, 70]. The inherent limitations of 2D VMC for strongman biomechanics research prompted the need to establish an alternative method.

Systematic Review 2 further expands on Question 1 *"What is already known about the biomechanics of athletes performing strongman exercises and where are the current gaps in the field of knowledge?"* by delving deeper into the biomechanics of strongman exercises and the practical applications of strongman biomechanics research.

Between-interval analyses were performed for the farmers walk [5, 30] and heavy sled pull [29, 32]. Between-exercise analyses were performed for the: log lift vs barbell clean and jerk [31]; log lift vs log lift of differing log diameter [69]; farmers walk vs unloaded walk [5]; farmers lift vs conventional deadlift [5]; and heavy sled pull vs back squat [32]. Joint/muscle kinetic analyses were performed between the atlas stone lift, log lift, tyre flip, farmer's walk, keg walk, suitcase carry and yoke walk [36]. Biomechanical performance determinants were only identified for the farmers walk [5, 30] and heavy sled pull [32] as well as the under-researched tyre flip [70].

The comprehensively researched strongman exercises and literature on traditional weight training exercises and common everyday activities were used to describe the expected biomechanical characteristics of under-researched strongman exercises. The yoke walk and atlas stone lift were identified as two of the most under-researched strongman exercises that strongman athletes typically perform in training and in competition [55]. Where the farmers walk could be characterised by smaller stride length and greater stride rate when compared to backpack load carriage and unloaded walking, it was suggested that further reductions in stride length and increases in stride rate would be observed during the yoke walk due to the greater loads typically carried by athletes performing the yoke walk. The atlas stone lift was suggested to share some biomechanical similarity with the traditional weight training exercises of the: Romanian deadlift (initial lift of stone from ground); box squat (initial explosive concentric movement from the bottom of the lap position); and front squat (concentric movement from a quarter squat position to lift completion where the stone is lifted on the anterior surface of the body).

The limited previous biomechanical data on the yoke walk and atlas stone lift may be somewhat reflective of the limited motion capture methods available to researchers at the time the studies were conducted (as identified in Systematic Review 1). For example, the collection of biomechanical data for exercises such as the yoke walk and atlas stone lift may not have been feasible using three-dimensional (3D) optical motion capture (OMC) or 2D VMC methods as a result of the distances covered (yoke walk typically being performed over 20 m) and/or implement-body-marker interference (both yoke walk and atlas stone lift).

The gaps in the current literature identified from Systematic Review 1 and Systematic Review 2 were: limited biomechanical data existing on athletes performing the atlas stone lift, yoke walk, tyre flip and vehicle pull; the lack of data of females performing strongman exercises; and the limited number of experienced strongman athletes included in previous strongman biomechanics research. Inertial motion capture was identified as a viable method to overcome the limitations of traditional motion capture methods such as 2D VMC when used for the biomechanical analysis of strongman exercises such as the yoke walk and atlas stone lift.

### 9.1.2 Technical Summary Literature Review

A technical summary assessing the current processing methodologies used for IMC (Chapter 5) was conducted to in-part answer Question 3 *"How may current inertial motion capture methods be used and further developed to characterise the biomechanics of athletes performing strongman exercises?"*. The Technical Summary Literature Review provides researchers with the background information required to implement an IMC approach, while providing a starting point for further development of IMC methods.

Five key components of IMC which must be considered when designing a methodology for a given application were highlighted: sensor fusion; position and orientation estimation; device placement; biomechanical modelling; and magnetometer calibration. Based on the discussion around the current implementation of each of these data processing components, an IMC methodology, suitable for the estimation of spatiotemporal and sagittal plane kinematic measures during functional fitness (more specifically strongman) exercises was devised. The methodology was devised to ensure practical implementation and further development by researchers with an intermediate Matlab skillset.

The advantages and disadvantages of the two main sensor fusion algorithms used in previous literature for inertial measurement unit (IMU)/magnetic angular rate and gravity (MARG) device orientation estimation, the Kalman filter and the complementary filter, were discussed. The Kalman filter was selected as the most appropriate means of sensor fusion for the applications of the PhD project due to its tunability for a given environment and movement speed, and its overall accuracy in orientation estimation [147]. The most significant drawback of the Kalman filter was identified as the greater computational load, and thus greater processing power required for onboard processing when compared to the complementary filter [154]. As onboard processing and live visualisation of data was not necessary for the application of the PhD project, this expense was redundant.

Various position and orientation sensor to segment alignment procedures were presented, specifically: anatomical alignment [138, 139], functional calibration [172, 174], static calibration [149, 178] and deep learning [150]. Of the presented procedures, the static calibration sensor to segment alignment procedure was adopted for the PhD project methodology due to its relative ease in implementation and accuracy in segment orientation estimation when compared to other, more complex procedures. Other sensor to segment alignment procedures required specialised alignment equipment or the device to be fitted by an experienced user (anatomical alignment), large sets of previous data (deep learning), or the performance of specialised movement patterns and computationally expensive numerical methods (functional alignment).

Spatiotemporal estimation was found to be achieved most commonly using either a biomechanical modelling [183] or strap-down integration approach [185]. As the strap-down integration approach takes into consideration multi-planar motion, strap-down integration using a zero-velocity update (ZUPT) and search-window thresholding approach was selected as the most appropriate data processing methodology for this PhD project. The ZUPT using a Kalman filter provided greater accuracy in drift correction and thus position estimation than the naïve ZUPT approach [181], while the search-window thresholding approach provided greater accuracy in gait event detection than a naïve thresholding approach [179].

In considering MARG device placement, soft tissue artefacts (STA) were identified as a source of error in traditional 3D OMC and IMC approaches. Where techniques have been developed for 3D OMC to reduce the effects of STA (algorithms, marker cluster sets) [194, 195], limited solutions have been proposed for IMC [196, 197]. For the applications of this PhD thesis, anatomical locations exposed to minimal STA were identified through iterative processes during pilot testing.

Potential differences in kinematic estimations between OMC and IMC caused by differences in biomechanical modelling assumptions between the methods were discussed. Optical motion capture typically relies on complex biomechanical models to estimate joint angular kinematics, whereas IMC methods use relative angle measures between the proximal and distal sensor to estimate joint kinematics [127]. As the developed IMC methodology used in this PhD project was intended to be implementable by a wide range of researchers, a minimal modelling approach, where relative device orientation was considered to be the estimation of the given joint orientation, was used.

Various magnetic disturbances were expected to be present within the gym data collection environment [203]. The reduction of noise and error caused by magnetic disturbance from the surrounding environment was acknowledged as an important component of the developed IMC methodology for the PhD project. A magnetic calibration procedure was implemented taking into consideration hard and soft iron effects and trial initialisation location and duration in order to minimise the noise and error.

Systematic Review 1, Systematic Review 2 and the Technical Summary Literature Review answered Question 1, Question 2 and in-part Question 3. Answering these questions assisted in establishing a basis for the methodological validation study and two strongman biomechanics experimental studies.

## 9.2 EXPERIMENTAL RESULTS AND PRACTICAL APPLICATIONS

One methodological validation study and two experimental studies were designed to answer Question 3, Question 4, Question 5 and Question 6. The results of these studies provided practical applications for strongman athletes, coaches and strength and conditioning coaches, and researchers and developers of IMC methodologies.

### 9.2.1 METHODOLOGICAL VALIDATION STUDY

The Methodological Validation Study (Chapter 6) set out to validate the IMC methodology recommended within the Technical Summary Literature Review (Chapter 5) and further answer Question 3 *"How may current inertial motion capture methods be used and further developed to characterise the biomechanics of athletes performing strongman exercises?"*.

Estimates of sagittal plane hip, knee and ankle joint angles and spatiotemporal parameters of stride length, stride duration and stance duration using the devised IMC method were assessed against a six-camera OMC system. Participants (n = 13) performed a variety of functional fitness exercises (squat, box squat, sandbag pickup, shuffle walk, bear crawl) chosen for their similarity to strongman exercises and ability to be performed within the limits of the laboratory environment, on a raised wooden floor.

Hip and knee range of motion (ROM) showed good to excellent agreement with the OMC system for the squat, box squat, and sandbag pickup, while ankle ROM agreement ranged from good to unacceptable. A tuned and filtered (TAF) method, where Kalman filter parameters were set by the researcher, was compared with a default (DEF) method, where default Kalman filter parameters were used. The TAF method generally outperformed the DEF method for estimation of hip and knee joint kinematics during the squat, box squat and sandbag pickup, while the DEF method outperformed the TAF method for estimation of ankle kinematics during these exercises. Although both DEF and TAF were accepted as valid methods, the better performance reported for the TAF method for hip and knee joint angular kinematics may reflect the suitability of the selected TAF tuning parameters for limbs experiencing greater angular velocity and ROM.

Hip and knee ROM MAPE for the shuffle-walk and bear crawl were reported to be unacceptable. Where small ROM (hip: 12.1 ± 3.3º; knee: 29.1 ± 8.9 º) was observed during the shuffle walk, it is suggested that the high noise to signal ratio in both OMC and the MARG method may be a primary factor contributing to the high MAPE. The inherent noise and measurement errors associated with each method are primarily derived from the differences in physical measures and biomechanical modelling assumptions used by each system to estimate joint kinematics.

Stride length, stride rate, and stance duration showed good to excellent agreement between OMC and IMC methods during both the shuffle walk and bear crawl. Difficulty in identifying the instance of initial contact and toe off during both the shuffle walk and bear crawl were suggested to be primary contributors to the spatiotemporal estimation error.

The minimal modelling MARG method presented in Chapter 6 is a useful method to measure the biomechanics of athletes performing strongman exercises. Current IMC methods may be further developed through the: standardisation of data processing methodologies and refinement of sensor fusion filtering parameters; development of biomechanical modelling methods; development of techniques for noise reduction and error caused by STA; and development of gait event detection thresholding techniques.

### 9.2.2 EXPERIMENTAL STUDY 1

Chapter 7 answers, part a) of the final three research questions. In answering Question 4, part a) *"What are the general biomechanical characteristics of the yoke walk?"*.

The biomechanical characteristics of athletes performing the yoke walk involved flexion of the hip and slight to neutral flexion of the knee at heel strike, slight to neutral extension of the hip and flexion of the knee at toe-off and moderate hip and knee ROM. The gait pattern of athletes performing the yoke walk was characterised by a shorter stride length and reduced stride rate and greater knee ROM and stance duration when compared to the previously researched strongman exercise, the farmers walk [30]. Such differences were suggested to be a result of the greater load carried in the yoke walk when compared to previous load carriage research.

The combination of an extended knee throughout the stance phase and a short stride length reduces the vertical displacement of the athlete's centre of mass (COM) [237], reducing the chance of "catching" the yoke on the ground, resulting in dropping the yoke. The metabolic efficiency gained through the reduced requirement to lift the total system load against gravity (as a result of the reduced vertical COM displacement), was suggested to be counterbalanced by the additional energy expenditure caused by an increase in stride rate to maintain velocity with a decreased stride length [238, 239]. A reduced vertical COM displacement may be particularly important when performing the yoke walk due to the naturally smaller ground-to-implement clearance and greater total system load being carried when compared with other strongman load carriage exercises such as the farmers walk.

In answering Question 5, part a) *"What are the biomechanical differences between different intervals of the yoke walk?"*.

Shorter stride length, stride rate, increased stance duration and lower average velocity was observed during the initial (0 – 5 m) interval when compared to the final three (5 – 20 m) intervals. The abbreviated lower limb motion, through greater flexion of the hip at toe off, greater flexion of the knee at heel strike and reduced knee ROM, is suggested to be a mechanism employed by athletes to attempt to rapidly increase stride rate during the acceleration phase. By rapidly increasing stride rate, the athlete is then able to increase their velocity through the optimisation of stride length (as a result of increased lower limb ROM) in the later (maximal velocity) intervals [254]. Based on the impulse momentum relationship, strongman athletes may benefit from performing ballistic training to develop the neuromuscular response required to generate maximal force during short periods of ground contact in the acceleration phase, to rapidly increase stride rate.

In answering Question 6, part a) *"Are there any biomechanical differences between male and female strongman athletes performing the yoke walk?"*.

No main between-sex differences were observed, while few two-way interactions between sex and interval were observed for the yoke walk. The lack of main between-sex spatiotemporal and sagittal plane joint kinematic differences observed during the yoke walk is in line with previous research using body-mass relative loading (≤ 30% body mass) [229] and relatively light absolute loads (i.e. 22 kg) [230] in load carriage tasks. Previous literature has, however, found a greater number of between-sex differences in frontal and transverse plane kinematics, which have been hypothesised as possible reason for the greater occurrence of anterior cruciate ligament and patellofemoral injuries reported in females [241, 242, 249]. Future research may be directed toward transverse and frontal plane kinematics analyses of male and female strongman athletes performing the yoke walk to assist in identifying any sex-specific injury risks associated with the yoke walk exercise.

#### 9.2.2.1 *PRACTICAL APPLICATIONS*

From the results of Experimental Study 1 it is suggest that strongman athletes and coaches and strength and conditioning coaches should look to focus on rapidly increasing stride rate during the initial intervals through an abbreviated lower limb ROM to assist in increasing velocity. Strongman athletes are recommended to perform exercises such as the concentric-only half-squat performed with maximal ballistic intent to develop the neuromuscular response required to generate maximal force during short periods of ground contact, resulting in the achievement of greater maximal velocity.

### 9.2.3 EXPERIMENTAL STUDY 2

Experimental Study 2 (Chapter 8) answers part b) of Question 4, Question 5 and Question 6. In answering Question 4, part b) *"What are the general biomechanical characteristics of the atlas stone lift?"*.

The atlas stone lift could be typically segmented into five phases: the recovery, initial grip, first pull, lap and second pull phase. The characteristics of athletes performing the atlas stone lift involved: maximal hip and moderate knee flexion and ankle dorsiflexion at the beginning of the first pull; moderate hip and knee flexion and moderate ankle plantarflexion at the beginning of the lap phase; moderate hip and maximal knee flexion and ankle dorsiflexion at the beginning of the second pull phase; and maximal hip, knee extension and ankle plantarflexion at lift completion.

Various phases of the atlas stone lift were identified as sharing similar kinematics with phases of the traditional weight training exercises of the Romanian deadlift and front squat [5, 269, 278]. The relatively short phase duration and large ROM observed for the initial pull phase of the atlas stone lift led to the suggestion that training for power and rate of force development during rapid extension of the hip and knee and to a lesser extent the ankle may promote physical adaptations required for greater performance of the first pull phase of the lift. Such similar training adaptations may be achieved by performing pulling derivatives of the clean and jerk or snatch, including the clean/power clean/snatch pull from the floor/knee or the mid-thigh pull [273, 283].

Greater strength adaptations may be achieved using a larger ROM [279]. The biomechanical similarity between the second pull phase of the atlas stone lift and the concentric phase of the front squat, yet greater ROM in the front squat, may suggest the front squat should be incorporated into the training programs of strongman athletes for greater strength adaptations while performing a similar movement to the second pull phase of the atlas stone lift.

Notable variation in the biomechanics of athletes performing the atlas stone lift deserve special mention and further investigation in future research. The zero-lap phase (one motion) technique appeared to be used by some athletes to save time in completing a repetition. Anecdotally, it appeared to be less critical for taller athletes to attain a high stone position on the chest (demonstrated by the zero-lap phase technique), as theoretically they are able to pass the stone over the bar at a lower height (as a percentage of their stature) than shorter athletes. Exploring the possible advantage taller athletes have in the atlas stone lift may be a particular area of interest for future research. The 'pop' and 'grind' techniques were used by some athletes at lift completion whereby the stone was either projected off the chest and over the bar (the pop) or moved with a small, positive vertical velocity upon approaching the height of the bar (the grind), respectively. This grind technique therefore appears to share some similarities to the concept of a sticking point/sticking region that has been examined previously in traditional resistance training exercises [284]. Future research could compare athletes who use these different stone lifting techniques to more clearly identify the biomechanical differences in their technique as well as the physical characteristics e.g., anthropometry, strength and power that may underpin these biomechanical differences.

In answering Question 5, part b) *"What are the biomechanical differences between each repetition of a set of atlas stones of incremental mass?"*.

The initial repetitions of the stone series were observed to be somewhat abbreviated versions of the later repetitions, whereby first pull phase hip and ankle ROM was generally smaller in repetition one than the final three repetitions. Lap phase hip and ankle ROM was also smaller in repetition one than the final three repetitions, and smaller in repetitions two and three (hip only) than repetition four. The abbreviated joint ROM during the initial repetitions in the series coincided with a reduction in the durations of most phases and total repetition time between the first two and final two repetitions of the set. The between-repetition biomechanical differences observed throughout the set were attributed to: the increase in mass of the stone; a likely self-preservation strategy used by the athlete to save energy and time; and a certain level of acute fatigue experienced by the athlete.

In answering Question 6, part b) *"Are there any biomechanical differences between male and female strongman athletes performing the atlas stone lift?"*.

When compared with male athletes, female athletes exhibited: greater hip flexion and ankle plantarflexion at the beginning of the first pull and greater overall hip ROM throughout the first pull; greater hip flexion and knee extension at the beginning of the lap phase, and smaller hip and ankle ROM throughout the lap phase; greater hip flexion, knee extension and ankle plantarflexion at the beginning of the second pull phase, and smaller knee ROM and greater ankle ROM throughout the second pull phase; and greater hip flexion and ankle plantarflexion at lift completion. With respect to the greater hip flexion at the beginning of the first pull phase, a contributing factor to this difference was suggested to be the differences in anthropometric ratios of the female and male population, where Keogh, et al. [280] reported statistically greater arm to leg length ratios in male powerlifters (67.8 ± 2.9%, n = 54) than female powerlifters (64.5 ± 2.5%, n = 14).

The greater hip extension displayed by male athletes at the beginning of the lap and second pull phase may be a mechanism used by male athletes to accommodate the larger diameter stones typically lifted by male athletes when compared to female athletes to ensure the COM of the stone remains as close as possible to their COM and within their base of support. This compensative mechanism employed by male athletes is likely to result in achieving a similar resistive moment arm about the lumbar spine when compared with female athletes. Male athletes, however, may experience a greater net joint moment about the lumbar spine due to the greater load typically lifted whilst maintaining a similar resistive moment arm length [34, 36].

#### 9.2.3.1 *PRACTICAL APPLICATIONS*

The results of Experimental Study 2 suggest that strongman athletes and coaches and strength and conditioning coaches should take advantage of the similarities identified between phases of the atlas stone lift and the traditional weight training exercises of the Romanian deadlift and front squat, and power adaptations achieved through pulling derivatives of the snatch and clean and jerk. By taking advantage of the similarity shared between the atlas stone lift and the identified traditional weight training exercises, greater training adaptations and thus performance in the atlas stone lift and its counterpart similar movements may be achieved.

## 9.3 LIMITATIONS

A number of limitations in the work contained within this PhD thesis should be acknowledged. Some potential limitations were identified in relation to the athlete population recruited, the strongman testing protocols and the data collection methodology used.

The athlete population recruited for Experimental Study 1 and Experimental Study 2 generally consisted of a greater number of experienced strongman athletes (combined sex and individual male and female athletes) than previous strongman biomechanics research. Although resulting in greater ecological validity of the results obtained, the requirement of participants to have a minimum of one strongman competition experience limited the number of athletes eligible to take part in the research. Where relatively high variance was observed in some of the biomechanical parameters for both the yoke walk and atlas stone lift, a greater number of participants in these strongman experimental studies would produce greater confidence (generalisability) in the results of the research.

Test protocols were established with the intention of using ecologically realistic training loads and carry distances. However, the way in which the yoke walk and atlas stone lift is performed in training can vary greatly depending on the relative standard of the athlete and the format of the competition for which the athlete is currently training. Greater ecological validity could be achieved by designing experimental protocols specific to a particular competition format. As the PhD project is the first research to describe spatiotemporal and kinematic characteristics of male and female strongman athletes performing the yoke walk and atlas stone lift, it was concluded that designing experimental protocols reflective of the common training forms of these exercises was most appropriate.

A limitation in the ecological validity of the devised IMC methodology arose due to the difficulty in selecting biomechanically similar exercises to the yoke walk and atlas stone lift in the Methodological Validation Study (Chapter 6). Loads used in the laboratory had to be minimised due to the laboratory having a raised wooden floor to accommodate an inset force plate. Qualitative analysis of the yoke walk suggested that due to the overall greater load being carried, athletes performing the yoke walk may exhibit shorter stride length, reduced stride rate and reduced lower limb ROM when compared to the farmers walk and unloaded walking [30, 98]. To achieve similar stride length, stride rate and lower limb ROM as the farmers walk, purely induced by loading, it was estimated that loads exceeding the load limit of the laboratory floor would be required. The research team concluded that instructing participants to walk with a modified "shuffle" gait pattern involving a relatively straight lower limb, small lower limb ROM and short stride length throughout the walk may result in a movement pattern biomechanically similar to the yoke walk.

In conducting yoke walk testing with ecologically valid loading, it became apparent that significantly larger lower limb ROM (yoke walk hip ROM: 37.9 ± 7.8º; shuffle walk hip ROM: 14.1 ± 3.7 º; yoke walk knee ROM: 53.9 ± 10.7 º; shuffle walk knee ROM: 22.9 ± 8.0 º) and stride length (yoke walk: 1.138 ± 0.171 m; shuffle walk: 0.326 ± 0.096 m) were exhibited by athletes performing the yoke walk than participants performing the shuffle walk in Chapter 6. As previous literature has suggested the validity of inertial motion capture methodologies to be dependent on the task complexity and ROM being measured [145, 260, 261], the validity of the IMC method used for the yoke walk may be greater than that observed for the shuffle walk in Chapter 6, laying somewhere between the squat, box squat and sandbag pickup (hip MAPE: 6.8 ± 6.1% – 8.2 ± 6.5%; knee MAPE: 3.7 ± 2.8% – 5.1 ± 3.7%) and the shuffle walk (hip MAPE: 25.1 ± 21.0; knee MAPE: 22.5 ± 16.5%). Without further validation using a movement which shares greater biomechanical similarity to the yoke walk, some care should be taken when interpreting joint angle kinematics of persons performing the yoke walk.

Spatiotemporal and kinematic estimates were measured for just a single side of the body during both the methodological validation and two experimental studies. Although only a minor limitation of the current PhD research, identification of biomechanical asymmetry may be key in identifying the presence of acute fatigue and/or reducing the risk of injury of athletes performing the atlas stone and yoke walk strongman exercises [285].

## 9.4 Future Research

As a result of undertaking the program of work within this PhD thesis, a number of areas of future work have been identified in the disciplines of IMC research and strongman biomechanics research.

Future work pertaining to the areas of IMC research may include:

- standardisation of data processing methodologies used for IMC to increase the rate of development of IMC;
- biomechanical modelling for joint kinematic analyses to produce kinematic estimations that better align with those obtained using OMC; and
- further development and implementation of methods toward the reduction of error caused by high noise to signal ratios and STA.

Future work pertaining to strongman biomechanics research may include:

- analyses comparing spatiotemporal and kinematic characteristics of higher and lower performing athletes performing the yoke walk and atlas stone lift, to directly identify biomechanical performance determinants of these exercises;
- kinetic analyses of the yoke walk and atlas stone lift when performed using ecologically valid loading, set and repetition schemes, to provide further insight into potential injury prevention and performance adaptation practices of strongman athletes, coaches and strength and conditioning coaches;
- multi-planar and bilateral biomechanical analyses of athletes performing the yoke walk and atlas stone lift;
- assessing the effects of yoke load and stone characteristics (including load, dimension, surface finish) on the biomechanics of strongman athletes;
- assessing the effect of anthropometrics on the biomechanics of athletes performing strongman exercises both dependent and independent of sex; and
- assessing the biomechanics leading to yoke drops and failed atlas stone lifts.

## 9.5 Conclusion

The aim of the PhD thesis was to develop, validate and use ecologically valid motion capture methods to describe the biomechanics of experienced male and female strongman athletes performing previously under-assessed strongman exercises, to better inform the practices of strongman coaches and athletes and strength and conditioning coaches.

In summary of the findings and in alignment with the aim of this PhD thesis, the following was demonstrated.

- Existing research into the relatively under-researched strongman exercises of the atlas stone lift and yoke walk may have been limited by traditional motion capture methods and as such, modern inertial motion capture methods may be used to expand the current biomechanical knowledge of strongman exercises.

- The biomechanics of athletes performing the yoke walk could be characterised by: 1) flexion of the hip and slight to neutral flexion of the knee at heel strike; 2) slight to neutral extension of the hip and flexion of the knee at toe-off; and 3) moderate hip and knee ROM. Athletes exhibited an abbreviated gait pattern with smaller joint ROM, shorter stride length, reduced stride rate, increased stance duration and lower average velocity during the initial acceleration phase when compared with the final three intervals.

- The atlas stone lift could typically be characterised by a recovery, initial grip, first pull, lap and second pull phase. Biomechanical similarity was shared with traditional weight training exercises of the Romanian deadlift (first pull) and front squat (second pull). Between-repetition biomechanical differences observed throughout the four-stone series were suggested to be in-part attributed to the increase in stone mass as well as acute fatigue.

- While few between-sex biomechanical differences were observed for the yoke walk, the between-sex biomechanical differences observed for the atlas stone lift were suggested to be, in-part, due anthropometric differences between sexes.

The results of this PhD thesis significantly contribute to the fields of inertial motion capture and strongman biomechanics research by: 1) demonstrating the feasibility of using inertial motion capture for the analysis of strongman exercises; and 2) providing the first spatiotemporal and kinematic description of both male and female strongman athletes performing the yoke walk and atlas stone lift exercises. It is anticipated that by using the information provided within this thesis, strongman coaches and athletes and strength and conditioning coaches will be better informed regarding how to prescribe training for, and coach their athletes performing the yoke walk and atlas stone lift. Researchers in the fields of strength-based sports biomechanics research and inertial motion capture research may also use the information provided within this thesis to structure future research in this area.

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# APPENDICES

# APPENDIX 1: INFORMED CONSENT, BH00070

EXPLANATORY STATEMENT

**Participant Informed Consent Form**

Project: The use of inertial-based devices for human motion capture
Project Number:
Ethics Application Number: BH00070

BOND UNIVERSITY
BRINGING AMBITION TO LIFE

FACULTY OF HEALTH SCIENCES AND MEDICINE

Bond University
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Australia

Toll free 1800 753 855
(within Australia)

Ph: +61 7 5595 4400
Fax: +61 7 5595 4122
(from overseas)

Email: hsm@bond.edu.au

ABN 88 010 694 121
CRICOS CODE 00017B

As part of the above Bond University research study, I have read the Explanatory Statement and I:
*(please tick box/s)*:

- ❑ am willing to take part in the study outlined in the Information for Research Participants sheet
- ❑ am willing to be videotaped performing the described exercises
- ❑ understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party.
- ❑ understand that my participation is voluntary and that I can withdraw freely at any stage of the project.
- ❑ understand that de-identified data from this research may be made available to other researchers.

Participant Name:........................................................................................ (please print)

Participant Signature:.........................................................................................................

Witness Name:....................................................................................................................

Witness Signature: .............................................................................................................

Date:............................

1

# Appendix 2: Informed consent, BH00045

EXPLANATORY STATEMENT

**Participant Informed Consent Form**

Project: Analysis of Strongman Biomechanics
Project Number:
Ethics Application Number: BH00045

BOND UNIVERSITY
BRINGING AMBITION TO LIFE

FACULTY OF HEALTH SCIENCES AND MEDICINE

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Ph: +61 7 5595 4400
Fax: +61 7 5595 4122
(from overseas)

Email: hsm@bond.edu.au

ABN 88 010 694 121
CRICOS CODE 00017B

As part of the above Bond University research study, I have read the Explanatory Statement and I:
*(please tick box/s)*:

- ❑ am willing to take part in the strongman study outlined in the Information for Research Participants sheet
- ❑ am willing to be videotaped performing the strongman exercises
- ❑ understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party.
- ❑ understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw freely at any stage of the project.
- ❑ understand that de-identified data from this research may be made available to other researchers.

Participant Name:........................................................................................ (please print)

Participant Signature:..........................................................................................................

Witness Name:......................................................................................................................

Witness Signature: ..............................................................................................................

Date:............................

1

# APPENDIX 3: CHAPTER 3 SUPPLEMENTARY MATERIAL

## SEARCH-TERM STRATEGY .DOCX

https://cloudstor.aarnet.edu.au/plus/s/zgVRJs13CIVLh6s

# APPENDIX 4: CHAPTER 6 SUPPLEMENTARY MATERIAL

## MARG AND OMC DATA

https://cloudstor.aarnet.edu.au/plus/s/uKrW0HlazGKIc3n

## APPENDIX 5: CHAPTER 7 SUPPLEMENTARY MATERIAL

### SUPPLEMENTARY TABLES

https://cloudstor.aarnet.edu.au/plus/s/n3yOnb59nuNDeL4

## APPENDIX 6: CHAPTER 8 SUPPLEMENTARY MATERIAL

### SUPPLEMENTARY TABLES

https://cloudstor.aarnet.edu.au/plus/s/nL5yvTmiEk1aBHr