Demands of the Kettlebell Snatch

Submitted by

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A thesis submitted in total fulfilment of the requirements of the degree of

Master of Exercise Science (Research)

School of Exercise Science

Faculty of Health Sciences

Australian Catholic University

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This thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No parts of this thesis have been submitted towards the award of any other degree or diploma in any other tertiary institution. No other person's work has been used without due acknowledgment in the main text of the thesis. All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees (where required). Further paragraphs will be included in the Statement of Authorship and Sources if applicable, specifying: (a) the extent of collaboration with another person or persons (b) the extent and the nature of any other assistance (e.g. statistical analysis, computer programming, editing) received in the pursuit of the research and preparation of the thesis.

James Alexander Ross   Date

Acknowledgements

There are so many people I need to thank, without whom this thesis would not have been possible to complete. Over the five years that I have worked on this research, many major life events have taken place. I closed one business and opened another, had shoulder surgery and even got married. Throughout this time my family, friends and supervisors were very patient and supportive.

To my lovely wife Laura, thank you for your tireless support - this wouldn't have been possible without your help.

Thank you to my ever supportive parents Elizabeth and Peter, who always encouraged me to pursue my interests and believed in me.

To Angus – I am so grateful for your time and help with data analysis.

Chris – thank you for shaping me into the student that I have become. I am so appreciative of your patience, the long chats, and freedom you gave me in my research endeavours.

To Cam – your assistance navigating VICON was crucial in my research. Thank you for your assistance in preparing my manuscripts, and helping to guide me through this process.

Thank you to Justin for agreeing to lend your expertise. Your time and effort has been invaluable to me, and a huge component my research.

Thank you to all the ACU students and staff, particularly Jeri and Stu for reviewing my thesis.

Lastly, a big thank you to Brett for his assistance throughout my candidature.

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List of Publications Related to this Thesis

Ross, J. A., Wilson, C. J., Keogh, J. W., Wai Ho, K., Lorenzen, C. (2015). Snatch trajectory of elite level girevoy (Kettlebell) sport athletes and its implications to strength and conditioning coaching. *International Journal of Sports Science and Coaching*, *10*(2-3), 439-452.

Ross J. A., Wilson C. J., Keogh J. W., and Lorenzen C. 2017. External kinetics of the kettlebell snatch in amateur lifters. PeerJ 5:e3111;DOI 10.7717/peerj.3111, 2017

List of conference presentations

Ross, J. A., Wilson, C. J., Lorenzen, C. Kettlebell snatch trajectory of elite level kettlebell sport athletes. – Congress of the European College of Sport Science ECSS - Barcelona 2013

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List of Abbreviations and Nomenclature

Maximum voluntary isometric contraction (MVIC)

Girevoy sport (GS)

Ground reaction force (GRF)

Electromyography (EMG)

Anterior-posterior (AP)

Medio-lateral (ML)

Absolute error (AE)

Radial error (RE)

Medio-lateral vertical (MLV)

Anterior-posterior vertical (APV)

Maximum voluntary contraction (MVC)

Heart rate (HR)

Respiratory exchange ratio (RER)

Rating of perceived exertion (RPE)

Body weight (BW)

Vertical (V)

Effect size (ES)

Cohen's D (ESD)

Cohen's F (ESF)

Prefix and Context

Upon the commencement of this research program, there was only one published study within Western scientific literature investigating the kettlebell snatch (McGill & Marshall, 2012). McGill and Marshall (2012) documented the myoelectrical activity of the kettlebell snatch and the internal kinetics of the spine to provide an insight into the safety of the kettlebell snatch for novice lifters. Thus, in addition to traditional means of research, coaches were liaised with within Australia and overseas in an effort to refine the research questions for this thesis. Additionally, coaching manuals were sourced and where necessary, translated to English. Trajectory was a common theme within barbell weightlifting research (Ho, Lorenzen, Wilson, Saunders, & Williams, 2014). Figure 1 is an image from a Russian text entitled '*Fundamentals of Kettlebell Sport: teaching motor actions and methods of training'*. Communications were made with the author to give context around the translation. A key discussion point was that the kettlebell trajectory of elite lifter's followed a narrower arc within the downwards phase compared to the upwards phase of the lift. This communication helped form one of the research questions for the first study. Furthermore, it was commonly accepted by many coaches that the overhead 'fixation' position is a resting position and that grip strength may diminish over the course of a set. However, discussions surrounding the trajectory with coaches helped formulate our questions within our second study about the intra-repetition analysis, as the end of the back swing was described as being a position of relative rest.

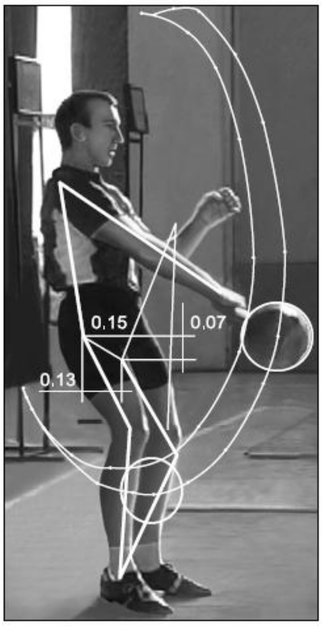

Рис. 11. *Траектория движения гири и перемещение тазобедренного сустава*

Figure 1. Kettlebell athlete performing the snatch. Taken from (Tikhonov, Suhovey, & Leonov, 2009)

Abstract

Kettlebell exercise has grown in popularity in the last decade. One of the exercises commonly performed is the kettlebell snatch, which is a key exercise within kettlebell sport. The kettlebell snatch involves swinging the kettlebell from between the legs to overhead in a continuous motion and is generally performed for multiple repetitions. In kettlebell sport the snatch is performed for up to ten minutes with only one hand change. A judge determines if the repetitions are performed correctly and allocates a point accordingly. Little research on the kettlebell snatch currently exists. When this thesis was started there was a single study, analysing the myoelectrical activity and internal kinetics of the spine (McGill & Marshall, 2012). During the course of this research program an additional three studies regarding the kettlebell snatch were published. Firstly, improvements in $\dot{V}O_2peak$ of the kettlebell snatch were investigated (Beltz et al., 2013). Secondly, a comparison was made between the external kinetics of the swing and snatch (Lake, Hetzler, & Lauder, 2014). Lastly, an intervention compared circuit training and kettlebell snatch intervals (Falatic et al., 2015). This research looks to further explore the kinetics and kinematics of the kettlebell snatch.

Study 1 (Chapter 3) recruited four international elite kettlebell sport athletes with the aim to gain insight into the trajectory and the variability of movement during four key points of the trajectory during the kettlebell snatch. In study 1, the lifters performed 16 repetitions of the kettlebell snatch with a 32 kg kettlebell over one minute. The analysis showed the kettlebells trajectory followed a ‘C’ path within both the upward and downward phases. There was a smaller ‘C’ path during the downwards phase and a larger ‘C’ path during the upwards phase. Moreover, there was low end point variability in the overhead lock out position, particularly within the vertical plane.

Study 2 (Chapter 4) aimed to quantify the external kinetics within amateur Australian kettlebell sport athletes within a six minute set. The snatch was found to produce differences in ground reaction forces between the ipsilateral and contralateral legs. The differences were found within the anterior-posterior (F (1.11) = 885.15 $p < 0.0001$, ESF = 7.00) and medio-lateral vectors (F (1.11) = 5.31, $p = 0.042$, ESF = 0.67). Finally, the peak mean force applied to the kettlebell was reduced when the first and last 14 repetitions were compared suggesting fatigue (F (1.11) = 7.42, $p = 0.02$, ESF = 0.45). This was further supported by decreased hand grip strength ($p = 0.001$, ESD = 0.77).

In summary, these studies provide a valuable insight into the kettlebell snatch. Study 1 showed that there is inter-individual difference within the kettlebells trajectory, however some key similarities exist within elite level athletes. 1) Low variability within the overhead position, 2) the kettlebell followed a ‘C’ shape within the upwards and downwards phase, 3) the downwards phase followed a narrow ‘C’ shape. Study 2 found that the kettlebell snatch imposed different demands upon each leg. Additionally, there were changes within the force applied to the kettlebell during a six minute set.

Chapter 1 - Introduction and Overview

The earliest record of the application of kettlebells as an exercise implement is from 17th century Russia, where strongmen used them to entertain crowds by performing feats of strength (Tikhonov, Suhovey, & Leonov, 2009; Tsatsouline, 2006). Prior to this, the primary purpose of the kettlebell was for use as a counterweight to weigh farming produce at the markets. Almost 300 years later, in 1948, the first kettlebell sport, or 'Girevoy sport' (GS) competition took place in Russia (Tikhonov et al., 2009). Participation in kettlebell sport and kettlebell training has grown significantly in the West throughout the past decade, becoming increasingly popular for both athletes and members of the general population. One exercise commonly performed is the kettlebell snatch, which is a key movement of GS.

Girevoy sport competition takes place on a platform like powerlifting or weightlifting. In Olympic weightlifting competition, the weightlifter will attempt three single repetitions of the barbell snatch followed by three single repetitions of the barbell clean and jerk. The winner of the event is the individual who lifts the combined maximum weight for the two lifts. In contrast, in GS, the kettlebell snatch is performed after the kettlebell jerk in biathlon or as a standalone event. The goal of the snatch within GS is to lift the kettlebell over the head successfully as many times as possible in ten minutes. The weight of the kettlebell is not changed throughout the entire competition. The biathlon is scored as the total number of repetitions from the two exercises, not total weight lifted. Both the kettlebell jerk and snatch are ten minutes in duration, with generally at least an hour between exercises. The snatch is considered the most technical event and is performed with one hand change permitted over the 10 minute set (IUKL, 2017). During GS competition, elite males perform the kettlebell snatch with a 32 kg weight, trained lifters use 24 kg and novices use 16 kg kettlebells. The current absolute world record stands at 238 snatches with a 32 kg kettlebell, within ten minutes (RKC, 2013). This record means that the world record holder averaged ~24 snatches with the 32 kg kettlebell per minute for 10 minutes, which equated to one snatch every 2.5 seconds.

Additionally, the snatch is performed by people outside of kettlebell sport to develop muscular power and muscular endurance, and is at times, part of circuit training. The kettlebell snatch may be a useful alternative to performing high repetitions of the barbell snatch. The unilateral and swinging nature of the kettlebell may provide a unique stimulus, and programming for higher repetitions will increase metabolic and grip demands (Beltz et al., 2013). The kettlebell snatch may have potential application in sports that require increased levels of local muscular endurance within the posterior chain (e.g. hamstrings, gluteals and erector spinae) and forearms. It has been proposed that athletes from grappling sports such as Judo and wrestling may benefit from this type of training (Barbas et al., 2011; Bonitch-Góngora, Bonitch-Domínguez, Padial, & Feriche, 2012; Branco et al., 2013; Kraemer et al., 2001).

The following sections will cover an overview of GS, a general description of the snatch technique, a comparison between the dumbbell and barbell snatch trajectory, an overview of the current state of the scientific understanding and a rationale for the need for research on the kettlebell snatch.

Chapter 2 - Review of Literature

Before the commencement of this research there was only one research paper that had examined the kettlebell snatch (McGill & Marshall, 2012). Currently, excluding the research presented in this thesis, there are only four studies reported in the literature on the kettlebell snatch. These studies have investigated the associated internal spinal kinetics and myoelectrical activity (McGill & Marshall, 2012), external kinetics (Lake et al., 2014), oxygen cost (Falatic et al., 2015) and strength adaptations (Beltz et al., 2013). These studies didn't investigate subjects that were highly trained with the kettlebell snatch. The body of knowledge available to coaches regarding this exercise is clearly limited. It was an aim of this thesis to investigate the trajectory and external kinetics of the kettlebell snatch within elite and trained kettlebell lifters.

2.1 Kettlebell Snatch and Swing Technique

Only one study has examined kettlebell snatch technique (McGill & Marshall, 2012). Novice participants were shown to extend the hips, knees and ankles simultaneously, and swing the kettlebell through the sagittal plane. From an integration of kinematics and EMG data, the kettlebell snatch was further described to have rapid muscle "activation-relaxation cycles", producing relatively large posterior shear forces on the spine (McGill & Marshall, 2012). It was suggested that both the kettlebell snatch and swing had these qualities. The authors also reported that the left latissimus dorsi, right gluteus maximus and erector spinae had the greatest normalised EMG. The left latissimus dorsi was reported to have the highest percentage of maximal voluntary contraction, despite the kettlebell being reported to be in the right hand. Which suggests that the latissimus dorsi may function to resist any extraneous trunk motion. However, there was considerable inter-lifter variability in some of the EMG amplitudes. This variability in EMG amplitudes may represent some aspects of functional variability or perhaps more likely reflect the limited training experience of the seven subjects who were described by the authors as ‘most having kettlebell training experience’ (McGill & Marshall, 2012). Currently, no English scientific literature exists on GS kettlebell snatch technique, thus a review of coaching manuals is necessary to have a better understanding of GS snatch technique (Rudnev, 2010). While there are other training manuals that exist, they are directed at the fitness industry, and describe a simplified version of the kettlebell snatch compared to that presented by GS coaches manual (Rudnev, 2010). The following sections describe the kettlebell snatch technique at the end point, downwards and upwards phases.

2.2 Starting Position and Overview of the Kettlebell Snatch

The kettlebell snatch has upwards and downwards phases within each repetition (Figure 2.1). For descriptive purposes it is useful to use the overhead lockout position as the starting and finishing position. The overhead lockout has also been termed “fixation” (Rudnev, 2010) . Successful fixation is important to score a point within GS. Fixation requires the athlete to stop and control the kettebell motion overhead for a brief period of time. During fixation, the handle of the kettlebell rests diagonally across the palm and the ball rests on the back of the wrist and forearm (Rudnev, 2010). From overhead fixation, the downwards phase is initiated with ‘the drop’, then the kettlebell handle moves from the palm into the fingers (‘re-gripped’), before moving into the ‘back swing’, where the kettlebell passes between the legs. In contrast, the upwards phase starts with the ‘forward swing’, then the ‘acceleration pull’ and lastly the ‘hand insertion’ phase.

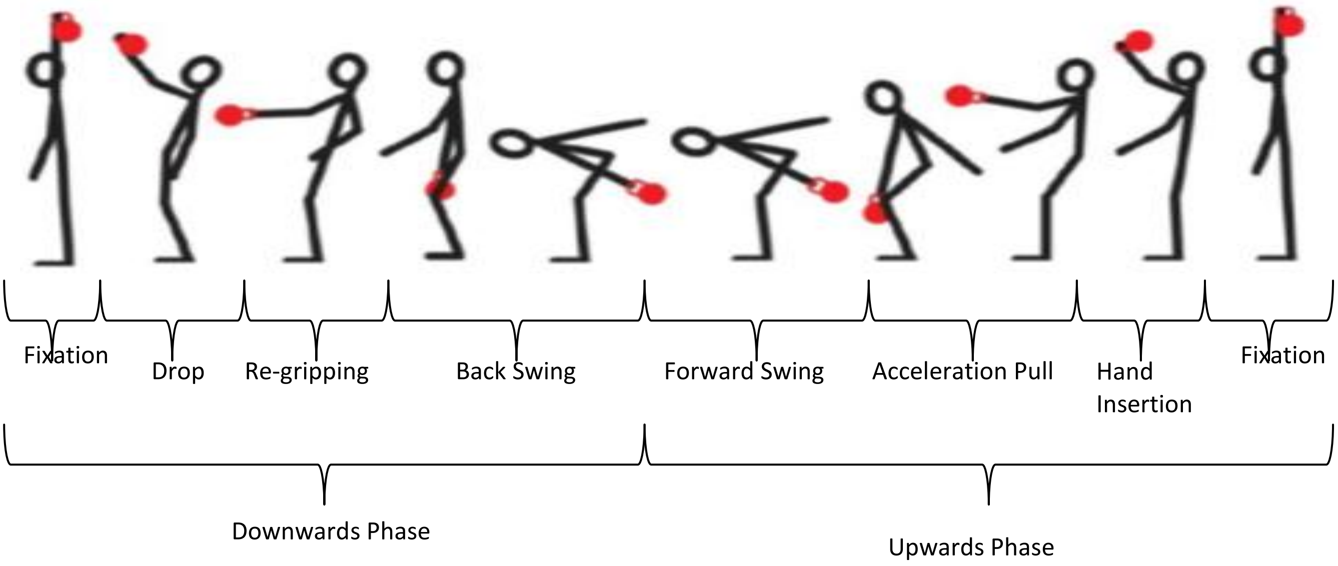

Figure 2.1. Phases of the kettlebell snatch

2.3 Downwards Phase of the Kettlebell Snatch

From the fixation phase, the drop takes place often with a counter movement away from the kettlebell. As the shoulder extends, moving the kettlebell away and downwards, the elbow supinates and flexes and then the lifter's arm straightens. During the re-gripping phase the elbow is extended as the athlete manoeuvres the handle from across the palm into the fingers. Once the elbow extends and the handle is in the fingers, the back swing phase begins. At the start of the back swing the torso remains upright, until the kettlebell passes between the legs. At this point the hips start to flex, and the knees extends slightly. The backswing phase comes to an end as the kettlebell reaches the apex, from there it moves into the forwards swing.

2.4 Upwards Phase of the Kettlebell Snatch

The forward swing position sees the kettlebell move between the legs by extending the hips, and slightly flexing the knees. The acceleration pull begins as the kettlebell passes through the knees and ends when the handle begins to move out of line with the arm. This is the most powerful motion in the snatch and has been described as having a "rapid contraction" (Rudnev, 2010). The acceleration pull involves knee and hip extension, ipsilateral torso rotation and elbow flexion. In the last stage of the upwards phase, the hand is inserted by moving the handle from the fingers to the palm. During the hand insertion phase, the elbow is extended and the torso rotates contralaterally. This rotates the kettlebell, moving the handle from the fingers to the palm and brings it into contact with the wrist and forearm (Figure 2.2). The kettlebell handle should rest diagonally across the palm which may help to reduce the extension movement during the fixation phase (Rudnev, 2010). Athletes will attempt to rest during the fixation phase, the goal has been described as to achieve “maximal relaxation” (Rudnev, 2010). The kettlebell comes to rest in the overhead position whilst in fixation, and the process is then repeated. These descriptions of the phases of the kettlebell snatch fit well with the findings of rapid contraction and relaxation cycles (McGill & Marshall, 2012). Anecdotally, beginners may perform the hand insertion phase poorly, causing unwanted impact of the kettlebell upon the distal forearm. Problems during this phase were noted within a web article, indicating that the issue may be widespread (Read, 2014). Overall, it has been suggested that in the upward and downward phases, the kettlebell follows somewhat different trajectories (Rudnev, 2010; Tikhonov et al., 2009).

Figure 2.2. Resting position of the kettlebell during fixation

2.5 Kettlebell Snatch Compared to Barbell and Dumbbell Snatch

The trajectory of the snatch performed with a kettlebell appears quite different to that of the snatch performed with barbells or dumbbells. The barbell snatch and power snatch has an 'S' shaped trajectory, characterised by an initial displacement of the barbell rearwards, then forwards and rearwards again (Stone, O'Bryant, Williams, Johnson, & Pierce, 1998; Winchester, Porter, & McBride, 2009). In contrast, the trajectory of a dumbbell power snatch is displaced forwards then rearwards when performed from the floor (Lauder & Lake, 2008). This is closer to a kettlebell snatch trajectory as the dumbbell can be pulled between the legs, whilst a barbell has to be manoeuvred around the knees. Within a strength and conditioning setting, the barbell snatch and dumbbell power snatch are typically performed for fewer repetitions (e.g. 1-5) to develop muscular power, whilst the kettlebell snatch is performed for a greater number of repetitions. Of the barbell snatch variations, the kettlebell sport snatch would most closely represent the hang power or hang muscle snatch variations. Hang refers to the starting position being off the floor and power involves a smaller range of motion of the lower body within the catch phase. Additionally, the muscle snatch only involves one leg extension and no second dip to receive the bar.

The dumbbell snatch has a greater velocity compared to the barbell power snatch ($3.17 m.s^{-1}$ vs. $2.18 m.s^{-1}$), at 80% of 1 RM (Lauder & Lake, 2008). In addition to having faster velocity, the dumbbell power snatch has been shown to impose different GRF upon the ipsilateral and contralateral legs (Lauder & Lake, 2008). For example, the contralateral side has a faster time to peak GRF during the pull and catch phases. In contrast, both legs of the barbell power snatch follow a similar pattern (Lauder & Lake, 2008). This suggests that performing the combination of unilateral upper body and bilateral lower body movements may result in a different stimulus, with respect to GRF for the ipsilateral and contralateral legs within the exercise. This may result in different adaptations for each leg, depending upon which hand the kettlebell or dumbbell is in.

One obvious difference between the barbell, dumbbell and kettlebell is the shape of the implement. The kettlebell has a displaced centre of mass and its handle allows it to hook over the wrist in the overhead fixation position. This may increase the risk of injury when performing 1RM efforts compared to the barbell or dumbbell snatch, as the kettlebell is harder to drop after the hand has been inserted with the handle sitting around the palm. This means that the kettlebell is effectively 'hooked' onto the upper limb. In contrast, the barbell and its plates are designed to be dropped more safely and easily as the weight sits above the wrist. As the barbell can easily roll out of the grip, this makes the barbell a more practical way to train single maximal efforts compared to training with a kettlebell. Additionally, load in the barbell snatch is more variable and only limited by the maximum weight added to the bar. This offers the athlete a greater variety of loads, in addition to smaller increments of progression.

With only four studies investigating the kettlebell snatch, there are large gaps in the literature. For example, the kettlebell velocity, kinetics and the trajectory have yet to be characterised or documented. An understanding of these areas will further coaching knowledge of training outcomes within this mode of training.

2.6 Energy Systems and Kettlebell Exercise

Improvements in aerobic and anaerobic endurance capacities following kettlebell training, have been reported in seven published studies (Beltz et al., 2013; Falatic et al., 2015; Farrar, Mayhew, & Koch, 2010; Hulsey, Soto, Koch, & Mayhew, 2012; Jay et al., 2011; Thomas, Larson, Hollander, & Kraemer, 2013; Williams & Kraemer, 2015). A summary of this research can be found table 2.1 (page 14). The kettlebell swing has received the most attention (Farrar et al., 2010; Hulsey et al., 2012; Jay et al., 2011), whilst the kettlebell snatch has had less (Falatic et al., 2015). The swing is of interest because it is similar to the bottom half of the snatch. From the midpoint to the backswing the snatch trajectory follows the same path as a kettlebell swing (re-gripping to acceleration pull within (Figure 2.1)). Additionally, GS athletes use the swing for specific conditioning for the snatch. The first kettlebell study investigated the use of the swing with 16kg at a self-selected pace with passive recovery over 12 minutes. In that time, 265 ± 68 repetitions were performed (Farrar et al., 2010). However, the subjects were recreationally active ($\dot{V}O_2max$ 52.78 ± 6.22 $ml \cdot kg^{-1} \cdot min^{-1}$) and not trained with the kettlebell swing, other than the single familiarisation session within this study. The protocol resulted in a maximum heart rate percentage that was significantly higher for a given level of oxygen consumption, when compared to the relationship recorded during the treadmill $\dot{V}O_2max$. Although it is unclear whether any pacing strategies were used, the mean respiratory exchange ratio (RER) was 1.0 ± 0.005, suggesting that they roughly paced on their lactate threshold (Farrar et al., 2010) and at an intensity theoretically sufficient to cause improvements in aerobic fitness.

In another study which controlled the work and rest periods, a comparison between 10 sets of kettlebell swings (35 second work:25second rest) was made with treadmill running in untrained subjects (Hulsey et al., 2012). The kettlebell swings were performed first, followed by the treadmill intervals, with the treadmill session matched to the intensity of the kettlebell swing intervals by rating of perceived exertion (RPE). Treadmill running was shown to require greater oxygen consumption compared to the kettlebell swing for males and females for a given RPE (Hulsey et al., 2012). A major limitation was that the subjects were new to the kettlebell swing, and were untrained other than their familiarisation sessions with this mode of training.

More recently it has been suggested that a moderate intensity kettlebell training protocol may be useful for people of low fitness (Thomas et al., 2013). Kettlebell swings and sumo deadlifts were alternated for three 10 minute sets eliciting a greater heart rate, blood pressure, and RPE at a similar oxygen cost to incline walking (Thomas et al., 2013). This exercise protocol resulted in a mean $\dot{V}O_2$peak of ~30 ml·kg^{-1}·min^{-1} within a group evenly split between healthy males and females with $\dot{V}O_2$max of 48.7 ± 6.9 ml·kg^{-1}·min^{-1}. A major limitation of this study was the metabolic cost of kettlebell exercise with the addition of the deadlift, as it doesn't allow for a direct comparison between incline treadmill walking and the kettlebell swing.

Interestingly, three intervention studies, each conducted over eight weeks had conflicting outcomes with regards to aerobic fitness improvements. A 15 minute session of 30 seconds of work with 60 seconds of rest, progressing to a 10 minute session of 30 seconds of work to 30 seconds of rest of kettlebell swing interval training was found to have no significant impact on aerobic fitness (Jay et al., 2011). Aerobic fitness was assessed via Åstrand's submaximal bike test method. Four possible reasons for the lack of improvement in the aerobic performance of this protocol included: 1) the mean training frequency was 2.1 sessions per week; 2) the training dosage was too small; 3) some of the subjects used no load swings or kettlebell deadlifts; and 4) sub-maximal testing was used to determine $\dot{V}O_2$max, a method which may not have been sensitive to discern a significant change. However, eight weeks of larger volume training resulted in a 13.8% improvement in $\dot{V}O_2$peak using a progressive kettlebell snatch test (Beltz et al., 2013). However, the improvement within this group may also be due to improvements in technique and not a training adaptation because there was also an increase in recorded maximal heart rate which isn't trainable. The larger volume intervention involved session durations between 45-60 minutes using the kettlebell for a greater range of exercises, including the snatch and swing. $\dot{V}O_2$peak was assessed before and after the eight weeks of kettlebell training. $\dot{V}O_2$peak was measured with an eight minute test using kettlebell snatch, starting a repetition per 9 seconds for the first minute, progressing to a repetition every 3 seconds in the 7^{th} minute and ending with a maximum effort. This test was found to elicit 41.3 ± 6.20 $ml \cdot kg^{-1} \cdot min^{-1}$ $\dot{V}O_2$peak, peak HR 190 ± 8.5 $b.min^{-1}$ and RER 1.24 ± 0.08. This increased from 36.3 ± 5.42 $ml.kg.min^{-1}$ $\dot{V}O_2$peak, peak HR 184 ± 13.8 $b.min^{-1}$ and RER 1.10 ± 0.11 at the beginning of the intervention. Despite having performed two familiarisation sessions, the increase in peak HR suggests that there was a learning effect as peak HR is not normally considered to be trainable. Another study that hasn't been published within the peer reviewed literature used a similar 10 minute progressive kettlebell snatch test that ended with 3 minutes of maximum effort, which was compared to a progressive row ergometer test. The kettlebell snatch was found to reach a $\dot{V}O_2$peak of 37.55 $ml \cdot kg^{-1} \cdot min^{-1}$, which was 82.1% of the rowing test (Chan, 2014). Further, sprint interval cycling for 30 seconds repeated 4 times was compared to a range of kettlebell exercises performed in a repeated 'Tabata' fashion (Williams & Kraemer, 2015). The kettlebell exercises had a greater mean $\dot{V}O_2$, whilst the sprint interval cycling had a higher $\dot{V}O_2$peak (Williams & Kraemer, 2015). A major limitation of this study was that the protocols were not matched for time, intensity and that there was a range of kettlebell exercises used. This prevents the ability to make direct comparison between the different modes of training. Also, subjects were described as "mostly" having had kettlebell and cycling experience. Additionally, 20 minutes of 12 kg kettlebell snatch intervals with 15 seconds of work, 15 seconds of rest was found to increase $\dot{V}O_2$peak by 6% assessed via cycle ergometer, with no increase within a circuit training group. These intervals were performed three times a week for four weeks at the pace of a five minute progressive kettlebell snatch set. These studies suggest that kettlebell training is less aerobically demanding than traditional modes of training such as running or cycling, however it may be more aerobically demanding than circuit training.

Table 2.1. Energy system kettlebell research

Study	Subjects	Intervention/protocol	Control	Outcome
(Jay et al., 2011)	40 Workers (laboratory technicians)	Eight weeks of interval training with kettlebells loads of 0-8 kg	Maintain current lifestyle	No increase in $\dot{V}O_2$ peak
(Beltz et al., 2013)	Male and Females Seventeen participants (9 male, 8 female) Resistance trained/recreationally active	Eight weeks of 30-45 minute of kettlebell training	Maintain current lifestyle	Increased HR and $\dot{V}O_2$peak a progressive kettlebell snatch set
(Falatic et al., 2015).	Eighteen female collegiate soccer players	4 weeks of Kettlebell snatch 15:15	4 weeks of Circuit training	Kettlebell snatch ↑ $\dot{V}O_2$max greater than circuit training
(Farrar et al., 2010)	Recreationally active males and females	12 minutes self paced kettlebell swings	Treadmill $\dot{V}O_2$max	For the same HR O_2 cost was 80% of the kettlebell swing
(Hulsey et al., 2012)	Thirteen subjects (11 male, 2 female) moderately trained with no with KBs.	Kettlebell swing 35 seconds of work 25 of rest	RPE matched treadmill	Treadmill running had ↑ O_2 cost, METS, Kcal.min^{-1}
(Thomas et al., 2013)	Ten novice volunteers (5 men; 5 women)	10 swings/10 deadlifts performed to a metronome for ten minutes with 3 minutes rest three times	$\dot{V}O2$peak matched incline treadmill walk for 10 minutes three times	Kb + deadlift had greater HR
(Chan, 2014)	Ten trained male participants	8 mins progressive snatch set	8 mins progressive rowing ergometer set	Rowing great $\dot{V}O2$ peak
(Williams & Kraemer, 2015)	Eight men with some prior experience with KB exercise and cycling	Four sets of 'Tabata' with kettlebell exercises	Four wingates – Set 1-2 four minutes rest, sets 3-4 two and half.	Higher $\dot{V}O2$ peak in the wingates, kettlebell 'Tabata' had higher energy expenditure

2.7 Kettlebell Swing Kinetics and Kinematics

There is limited information available on the kinetics of the kettlebell snatch, with one study comparing the kinetics of the kettlebell swing and kettlebell snatch (Lauder & Lake, 2008). The comparison found that the vertical impulse was not significantly different between the two exercises. The kettlebell swing was found to have greater horizontal impulse than the kettlebell snatch. Strength and conditioning coaches may wish to prescribe the kettlebell swing over the snatch for greater vector specificity. A limitation of this work is that the GRF was tested on only one force plate. As the kettlebell snatch provides a unique stimulus to each leg, similar to the one armed dumbbell snatch, which has been found to affect the loading of each leg (Lauder & Lake, 2008), it is also possible that such differences would be seen in the kettlebell snatch.

A number of studies have investigated the effect of the kettlebell swing on strength and power. Three intervention studies (Jay et al., 2013; Lake & Lauder, 2012a; Otto III, Coburn, Brown, & Spiering, 2012), concluded that the swing exercise can improve jump performance. Kettlebell training was also considered to transfer to weightlifting and powerlifting exercises (Manocchia et al., 2010) improve leg press and grip strength (Beltz et al., 2013) and increase back extensor strength (Jay et al., 2011). A summary of this research can be found in table 2.2 (page 17).

Three kettlebell swing variations were compared to weightlifting exercises (Otto III et al., 2012). Both groups significantly improved power clean performance, although the weightlifting group had greater improvements in back squat (Otto III et al., 2012). It is important to note that the kettlebell group only used a 16 kg load and the weightlifting group had individual RM loading, ranging from 4-6RM which was increased weeks 4-6. The improvements in vertical jump performance and body composition were similar in both groups (Otto III et al., 2012). Thus if limited equipment is available to a strength and conditioning coach, a 16 kg kettlebell will allow for the training of strength and power. Further, the kettlebell swing with a 32 kg kettlebell produced significantly less peak force than the back squat performed at 60% and 80% of 1RM; and the 16 kg kettlebell swing produced less force than the 40% 1RM back squat (Lake & Lauder, 2012b). However, the kettlebell swing with the 32 kg was not statistically different in the peak force output of the back squat with 20% and 40% of 1RM loads or with the mean force with 20%, 40% and 60% 1RM loads (Lake & Lauder, 2012b). These kinetic findings would support the commonly held view that back squatting with heavy loads would increase strength more than kettlebell swings with 16-32 kg (Lake & Lauder, 2012b). Interestingly, the back squats all had significantly less impulse, mean and peak power outputs than that of the swing with the 32 kg. There was no significant difference in the peak and mean power output of the 32 kg swing compared to jump squat with 0%, 20%, 40% and 60% 1RM (Lake & Lauder, 2012b). This would further support that the kettlebell swing would be a useful exercise for developing muscular power.

In terms of intervention, six weeks of jump squat training at individualised maximum power output was compared to kettlebell swing training (Lake & Lauder, 2012a). Within the individualised group four subjects performed the jumps with body weight, four subjects used 20%, one subject used 40% 1RM and three used 60% 1RM. This was compared to 12 kg kettlebell swings if body mass was <70 kg and 16 kg if body mass was >70 kg. It was found that the jump squat and kettlebell swing groups both significantly improved back squat and vertical jump performance. However, the kettlebell group had a larger effect size improvement of 0.81 compared to 0.43 for the back squat, whilst the jump squat group had a larger effect of 0.83 to 0.60 in vertical jump performance (Lake & Lauder, 2012a). The kettlebell swings were performed for 12 minutes with 30s of maximal repetitions followed by 30s rest. In contrast, the jump squats were performed for fewer repetitions ranging from 8 x 6 for the body weight jump squats to 4 x 3 for the 60% 1RM group (Lake & Lauder, 2012a). Possible reasons for greater transference to back squatting for the kettlebell group could be the difference in volume or kinematic differences. They suggest that the kettlebell swing targeted the posterior chain to a greater extent, which plays an important role in back squat performance. The kettlebell swing has been shown to cause fatigue within the spinal erectors despite the limited range of motion they move through, which further strengthens this hypothesis (Edinborough, Fisher, & Steele, 2016). Additionally, as the vertical jump and jump squat share many kinematic and kinetic similarities it is not surprising that the jump squat training resulted in a greater improvement in vertical jump than that observed with the kettlebell swing. A major limitation within these studies is how the kettlebell swing is prescribed compared to traditional exercises.

Table 2.2. Strength and power kettlebell research

Study	Subjects	Intervention/protocol	Control	Outcome
Lauder & Lake, (2008)	16 males with a minimise of 6 month of training with kettlebell	Kettlebell swing 16 kg, 24 kg, 32 kg	Back squat 40%, 60%, 80% 1RM Jump squat 20%, 40%, 60%	Back squat had greater peak force Similar power between 32 kg swing and 40% jump squat 1RM Greater impulse within the 32 kg swing group
Manocchia et al., (2010)	37 males and females with 6 months of resistance training	Kettlebell training 2 days a week for 10 weeks	Maintain current lifestyle	KB increase 3RM clean and jerk and 3RM bench press
Jay et al., 2013	40 workers (laboratory technicians)	Weeks 1-4 30:60 kettlebell swing, week 5-8 kettlebell swing 30:30	Maintain current lifestyle	Increase in vertical jump performance greater than baseline, but not more than control
Otto III, Coburn, Brown, & Spiering, (2012)	Thirty healthy men (19–26 years) with at least 1 year of resistance training experience	6 weeks of kb exercises	6 weeks of barbell weightlifting	Barbell had great squat strength, no difference in body comparison or vertical jump
Lake & Lauder, (2012)	At least of 3 months resistance training experience	30:30 x 12 kb swings	vertical jump at optimal power	Swing had greater increase in back squat Vertical jump had a greater increase in CMJ
Beltz et al., (2013)	Male and Females Seventeen participants (9 male, 8 female) Resistance trained/recreationally active	Eight weeks of 30-45 minute of kettlebell training	Maintain current lifestyle	Increased leg press and grip strength

2.9 Rationale

To date there has been very little research on the technical and physical demands of the kettlebell snatch. Only four published studies aside from this research program currently exist. The aim is to add to the limited literature and provide an understanding of the kettlebell trajectory and external kinetics of the kettlebell snatch. Improved knowledge within these areas may help inform coaches both within and outside GS. A comparison between external kinetics of the ipsilateral and contralateral legs will elucidate the differing demands placed upon the body. Additionally, intra repetition analysis of force applied to the kettlebell will offer insight into temporal changes in external kinetics. A comparison of external kinetics within the kettlebell snatch over the course of a six minute exercise bout will be made to determine if there is significant change within kinetics within this time frame.

Chapter 3 - Study 1: Snatch Trajectory of Elite Level Girevoy (Kettlebell) Sport Athletes and its Implications to Strength and Conditioning Coaching

Publication statement:

This paper was accepted for published in the *International Journal of Sports Science and Coaching*:

Ross, J. A., Wilson, C. J., Keogh, J. W., Wai Ho, K., Lorenzen, C. (2015). Snatch trajectory of elite level girevoy (Kettlebell) sport athletes and its implications to strength and conditioning coaching. *International Journal of Sports Science and Coaching*, *10*(2-3), 439-452.

3.1 Abstract

Girevoy sport (GS) has developed only recently in the West, resulting in a paucity of English scientific literature available. The aim was to document kettlebell trajectory of GS athletes performing the kettlebell snatch. Four elite GS athletes (age = 29-47 years, body mass = 68.3-108.1 kg, height 1.72-1.89 m) completed one set of 16 repetitions with a 32.1 kg kettlebell. Trajectory was captured with the VICON motion analysis system (250 Hz) and analysed with VICON Nexus (1.7.1). The kettlebell followed a 'C' shape trajectory in the sagittal plane. Mean peak velocity in the upwards phase was 4.03 ± 0.20 m s^{-1}, compared to 3.70 ± 0.30 m s^{-1} during the downwards phase, and mean radial error across the sagittal and frontal planes was 0.022 ± 0.006 m. Low error in the movement suggests consistent trajectory is important to reduce extraneous movement and improve efficiency. While the kettlebell snatch and swing both require large anterior-posterior motion, the snatch requires the kettlebell to be held stationary overhead. Therefore, a different coaching application is required to that of a barbell snatch.

Key words: Kettlebell, Resistance Training, Snatch

3.2 Introduction

Kettlebell exercise was initially seen at the end of the 17th century in Russia, where strongmen used 16 kg, 32 kg and 48 kg kettlebells to demonstrate feats of strength at fairs, festivals and circuses (Tikhonov et al., 2009; Tsatsouline, 2006). The first kettlebell sport, or 'Girevoy sport' (GS) competition was held in 1948 and fourteen years later, GS was included into the national sports of Russia (Tikhonov et al., 2009). Over the past 10 years, kettlebell training has become increasingly popular as a form of resistance training for athletes and members of the general population, coinciding with increased participation in GS competition. Whilst the versatility of kettlebells allows the performance of many exercises; swings, jerks, clean and jerks, and snatches are some of the most commonly performed kettlebell movements.

The snatch is typically performed with a barbell in Olympic weightlifting events, although dumbbell and kettlebell versions are becoming more popular. The kettlebell snatch is performed in a biathlon or as a standalone event in GS competitions. The competition takes place on a weightlifting platform and has a time limit of 10 minutes per set. The biathlon is scored as the total number of repetitions performed from two exercises: the jerk followed by the snatch, each of 10 minutes duration, with at least an hour between exercises. The snatch is performed with one hand change permitted per set and is considered the most technical event in GS (Tikhonov et al., 2009). Elite individuals perform the kettlebell snatch with a 32 kg kettlebell during the 10 minute competition, with the current absolute world record standing at 238 snatches.

It has been suggested that kettlebell training is a useful mode of training to improve aerobic fitness (Beltz et al., 2013; Farrar et al., 2010; Hulsey et al., 2012),vertical jump (Jay et al., 2013; Lake & Lauder, 2012a, 2012b; Otto III et al., 2012) and back squat performance (Lake & Lauder, 2012a; Otto III et al., 2012). Previous research utilising a 32 kg 2-handed kettlebell swing demonstrated similar power outputs and a larger impulse, compared to the jump squat with 40% 1RM (Lake & Lauder, 2012b). A training study comparing the chronic effects of kettlebell swings and jump squats was reported to significantly improve vertical jump and back squat 1RM. However, the kettlebell group had a smaller improvement in the vertical jump, yet larger improvement in back squat performance (Lake & Lauder, 2012a). Of the two interventions that investigated the effects of kettlebell training on the cardiorespiratory system, only one found improvements. It is possible that the reason for the lack of improvement was due to the low training dosage of 10-15 minutes three times a week with 70% adherence (Jay et al., 2011). In contrast, 30-45 minutes of training twice a week, using a combination of kettlebell exercises including the snatch, was found to improve $\dot{V}O_2$peak by 13.8% during a progressive kettlebell snatch set (Beltz et al., 2013).

Generally, only qualitative descriptions of the kettlebell snatch during elite performance are available. The International Kettlebell Sport & Fitness Academy has described the snatch as comprising six components (Rudnev, 2010). As seen in Figure 3.1, the start and finish are referred to as “fixation”. This is where the kettlebell is locked out overhead. The three components of the downwards phase include: the drop, re-gripping, and back swing, while the upwards phase involves the forward swing, acceleration pull, and hand insertion (refer to Figure 3.1).

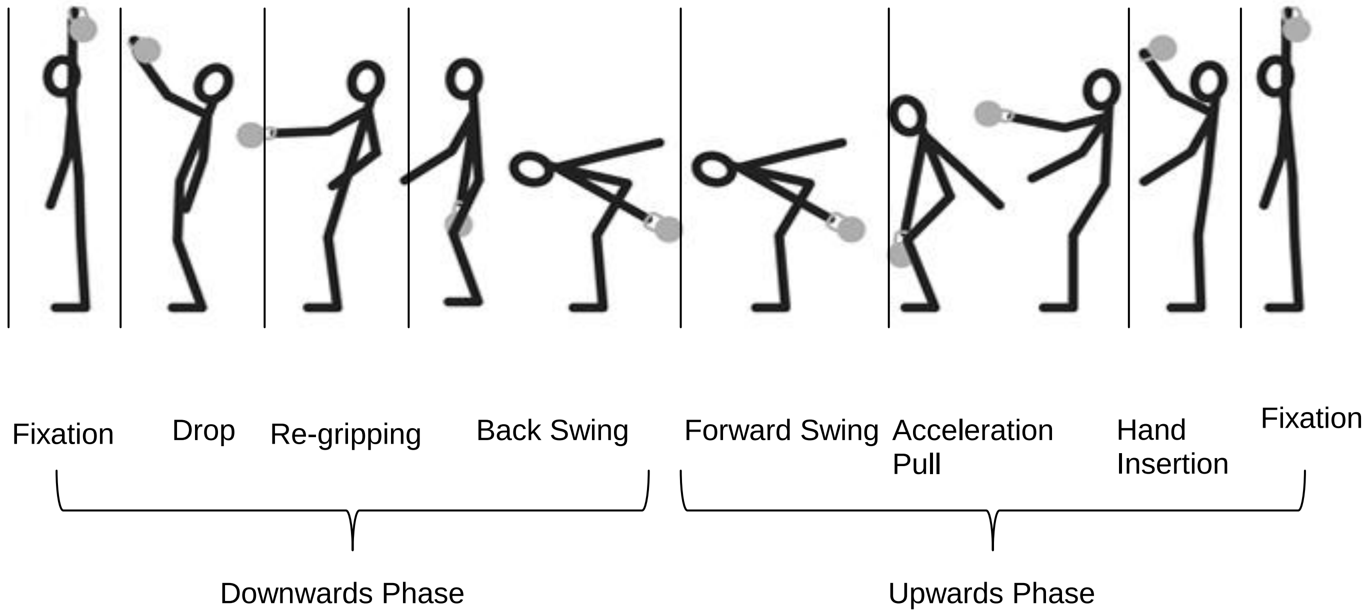

Figure 3.1. Phases of the kettlebell snatch

Figure 3.2 outlines key points within the kettlebells trajectory, point 1 represents fixation. In this position, the handle of the kettlebell rests diagonally across the palm and the ball rests on the back of the wrist and forearm (Rudnev, 2010). The drop is initiated by a counter movement of the torso away from the kettlebell. At approximately the same time, the shoulder begins to extend, and the elbow supinates and flexes (Rudnev, 2010; Tikhonov et al., 2009). Between the 'drop' and the 'back swing' the handle is repositioned (re-gripped) from the palm to the fingers (Rudnev, 2010). This portion of the downwards trajectory is indicated at approximately Figure 3.2, point 2. At the start of the back swing the knees are slightly flexed and the torso remains upright, until the kettlebell passes between the legs, whereby the hips flex and the knees extend (finishing at Figure 3.2, point 3). The forwards swing phase consists of the kettlebell moving forward between the legs via hip extension and knee flexion. The acceleration pull (approximately Figure 3.2, point 4) begins as the kettlebell passes the knees. This is the most powerful motion in the snatch, and involves knee and hip extension, ipsilateral torso rotation and elbow flexion (Rudnev, 2010). It ends when the kettlebell is once again re-gripped (hand insertion). During the hand insertion phase, the elbow is extended and the torso rotates contralaterally (Rudnev, 2010). This rotates the kettlebell, moving the handle from the fingers to the palm, bringing it into contact with the wrist and forearm (Rudnev, 2010). The kettlebell comes to rest in the overhead position whilst in fixation, and the process is then repeated (see Figure 3.1). It has been suggested that in the upwards and downwards phases the kettlebell follows somewhat different trajectories (Tikhonov et al., 2009). To our knowledge, only one study has examined the technique of the kettlebell snatch (McGill & Marshall, 2012), reporting that novice participants extend the hips, knees and ankles simultaneously, and swing the kettlebell through the sagittal plane. The kettlebell snatch was further described to have rapid muscle activation-relaxation cycles, producing relatively large posterior shear forces on the spine (McGill & Marshall, 2012).

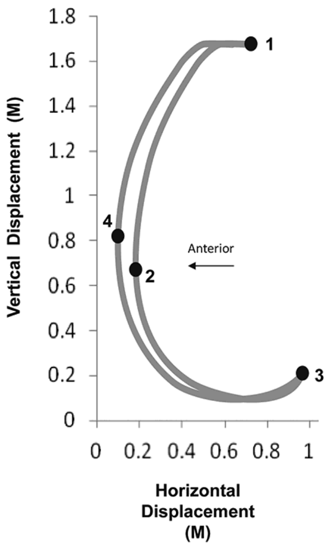

Figure 3.2. An example of the four points of error in the kettlebell snatch. 1 - fixation, 2 - midpoint of the downwards phase, 3- end of the back swing, 4 – midpoint of the upwards phase.

This proposed trajectory of the snatch performed with a kettlebell appears quite different to that of the snatch performed with barbells or dumbbells. The barbell snatch and power snatch has been shown to follow an ‘S’ or reverse ‘S’ shaped trajectory, characterised by an initial small displacement of the barbell rearwards, then forwards and rearwards again (Stone et al., 1998; Winchester et al., 2009). This type of trajectory allows the weightlifter to move through the first pull and transition phase, and to adopt the power position prior to the second pull. The power position may allow for the generation of very large power outputs during the second pull (Garhammer, 1993). Elite weightlifters were found to have an anterior posterior range of -0.096 ± 0.07 m during successful barbell snatch attempts. In contrast, the trajectory of a dumbbell power snatch is displaced forwards then rearwards (Lauder & Lake, 2008).

During competition, the barbell snatch is performed with a bilateral grip for one maximal repetition. Conversely, the kettlebell snatch is performed unilaterally and traditionally utilises multiple repetitions in competitions. The duration and technique used in the upwards and downwards phases may both be of importance. Additionally, the kettlebells displaced centre of mass sits below the wrist. This makes it much harder to safely fail a single maximal lift of a kettlebell snatch, compared to that of a barbell or dumbbell snatch. This suggests the kettlebell snatch is better suited to higher repetitions than the barbell snatch and as such may be a better tool for increasing energy expenditure and developing aerobic and anaerobic conditioning.

In comparison to the barbell snatch, the unilateral nature of the kettlebell snatch allows for greater degrees of freedom, which may result in a larger choice of techniques. However, the unique shape of the kettlebell may necessitate a modified approach to training and technique, in contrast to that of a barbell. The material and body of knowledge available to coaches regarding kettlebell exercises for training purposes is limited. The present study aimed to investigate the kettlebell trajectory of elite kettlebell lifters during the snatch. This information is especially important for coaches and strength and conditioning specialists looking to prescribe higher repetition snatch movements for their athletes. As a training tool, the kettlebell snatch may be better suited to higher repetitions. Additionally, the kettlebell snatch is commonly performed with a cadence which may further contribute to it being a novel stimulus. Comparatively, this may require different applications to that of the barbell snatch, traditionally utilising one repetition in competition.

3.3 Method

3.3.1 Testing Procedures

Four elite participants performed 16 repetitions over one minute with one 32 kg kettlebell. Repetitions 2-16 were compared to help determine the variation in the trajectory as these repetitions all had a downward phase preceding the upward. Kettlebell trajectory was captured with the VICON Motion Analysis System (250 Hz) and analysed with VICON Nexus (1.7.1). The cadence of 16 repetitions per minute was selected based on similar cadences sustained during either training or competition.

3.3.2 Participants

Four elite kettlebell sport athletes (originating in Russia or Kyrgyzstan), who had all won at least one world championship in biathlon (jerk and snatch) and/or held past or current world records in the snatch, were recruited. In their most recent competition, which occurred within 12 months of data collection, all lifters performed between 80-100% of the current world record number of lifts with a 32kg kettlebell for their respective weight categories. All participants held the rank of 'Master of Sport International Class' or 'Honored Master of Sport', (as issued by the Ministry of Sports of Russia, or the USSR State Committee for Physical Culture and Sport). The four participants had the following characteristics: age = 29-47 yr, body mass = 68.3-108.1 kg, and height = 1.72-1.89 m. This study was approved by the

Institutional Review Board. Informed consent was given, in the presence of a translator if required.

3.3.3 Procedures

Six VICON infrared cameras were placed around a weightlifting platform in a position to capture three dimensional motion of the kettlebell during the snatch. The infrared cameras captured the movement of reflective markers placed on the kettlebell. The system was calibrated dynamically by waving an L-wand with five reflective markers in the area that the kettlebell would pass through, in accordance to the manufacturer's instructions. This was repeated until all cameras had an RMS error under 0.2% (Ho, Williams, Wilson, & Meehan, 2011). The point of origin was then set in the middle of the platform, to calibrate the cameras positions. A professional-grade kettlebell (Iron Edge, Australia), with a mass of 32.1 kg was used as its dimensions are the standard requirement for kettlebell sport. Markers (14 mm x 12.5 mm in diameter) were placed on the kettlebell at the base of each handle to avoid contact with the athlete and to ensure consistent position. Participants were required to perform a warm-up they would typically perform prior to performing the kettlebell snatch. Chalk, sand paper and a spray bottle were provided to ensure that the handle was prepared to their individual lifting requirements. After the marker set had been placed, each lifter stood on a platform and performed one set of snatches for 16 repetitions over 1 minute with their self-selected hand. This pace was selected as it was the competition pace for one or more of the athletes, was attainable by novice and intermediate athletes (albeit with lighter loads), and commonly performed in training and competition. An analogue clock was placed in view to allow consistent pace.

Kettlebell trajectory was subsequently determined by attaining the midpoint of the two markers. After each trial had been performed the markers were manually labelled using

VICON Nexus software. A frame-by-frame review of each trial was undertaken to ensure there was minimal error caused by unlabelled markers. After this review took place a Woltering spline filter was applied to fill any gaps (less than 20 frames) in the trajectories (Woltring, 1986). These gaps in the trajectories were calculated by the markers past trajectory, velocity and acceleration.

Time displacement data were used to determine the trajectory and velocity in three dimensions of motion. For ease of interpretation resultant velocity was used. Four points of each repetition of the kettlebell trajectory were analysed: 1) fixation; 2) midpoint of the downwards phase; 3) end of the back swing; and 4) midpoint of the upwards phase (see Figure 3.2).

These four points were identified the moment the kettlebells trajectory changed from an anterior to posterior direction, or vice versa. The mean position from all 15 repetitions at these four points was the goal position. These four points were used as a reference to determine the error in one and two dimensions. At these four points of error (figure 3.2), absolute error (AE, including vertical error, anterior-posterior error and medio-lateral error) illustrated the distance in metres from the goal in one dimension (Magill, 1998). The radial error (RE, including sagittal plane error and frontal plane error) signified the distance in metres from the goal in two dimensions (Magill, 1998). The RE was calculated by using the following formula:

Equation 1. (RE in the sagittal plane = $\sqrt{(Vertical\ error)^2 + (Anterior\ Posterior\ error)^2}$)

Equation 2. (RE in the frontal plane = $\sqrt{(Vertical\ error)^2 + (Medio - Lateral\ error)^2}$)

The anterior-posterior (AP), medio-lateral (ML) and vertical displacements were calculated from the end of the back swing to the midpoint of the trajectory for AP and ML, and to fixation for the vertical displacement range. Comparisons in the lifters' trajectories were also made using an anterior-posterior to vertical ratio (APV), and medio-lateral to vertical (MLV) ratio. The end of the back swing to fixation mean displacement range was used to determine the vertical portions of the ratios.

3.3.4 Statistical Analyses

Data has been presented as means and standard deviations unless stated otherwise. Descriptive statistics were used to determine the amount of kettlebell AP, ML motion and variation for each lifter. Effect size (ES) and paired t-tests with two tails were used to compare the midpoint of the upwards and downwards phases for each repetition. The magnitude of the effect was considered trivial ES <0.2, small ES 0.2-0.6, moderate 0.6-1.2, large ES 1.2-2.0, very large ES 2.0-4.0 and extremely large ES > 4.0 (Hopkins, 2010). The AE and RE for repetitions 2-16 were calculated. The first repetition was ignored because it started from the ground and not in fixation. The variation was determined at the same four points, listed above. AE was calculated in AP, ML and vertical planes of motion. RE was calculated in the sagittal and frontal planes.

3.4 Results

3.4.1 Trajectory

In the sagittal plane, the trajectory of the kettlebell snatch followed a C-path for all participants through the upwards and downwards phases (Figure 3.3). Figure 3.3 illustrates the kettlebell sagittal plane trajectory for the four subjects, whilst Figure 3.4 represents the kettlebell trajectory in the frontal plane of motion.

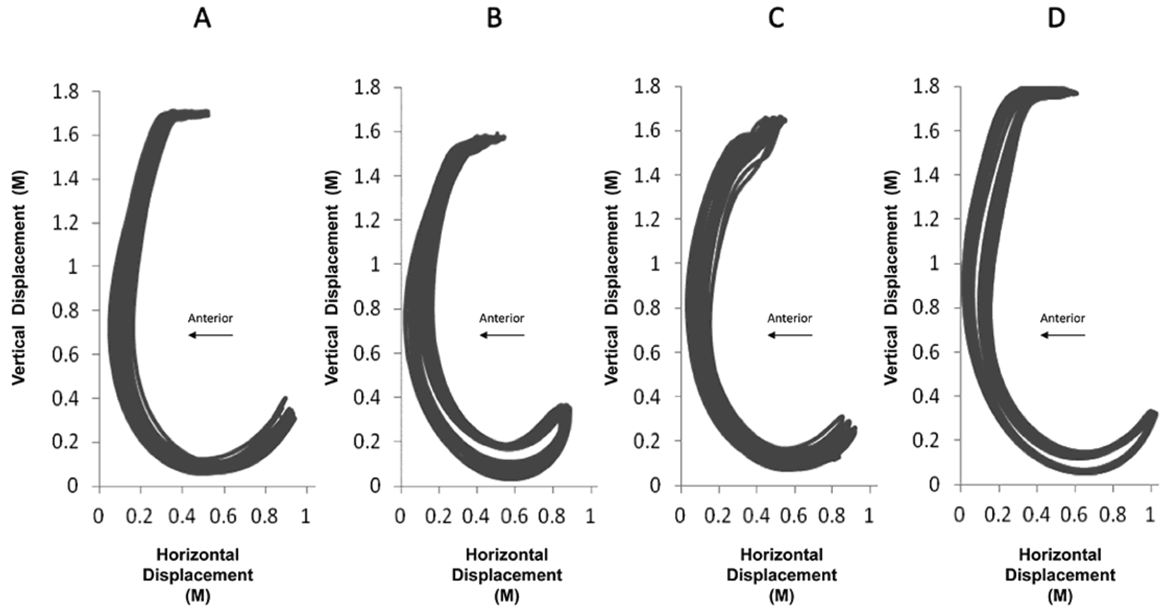

Figure 3.3. Sagittal plane kettlebell trajectory

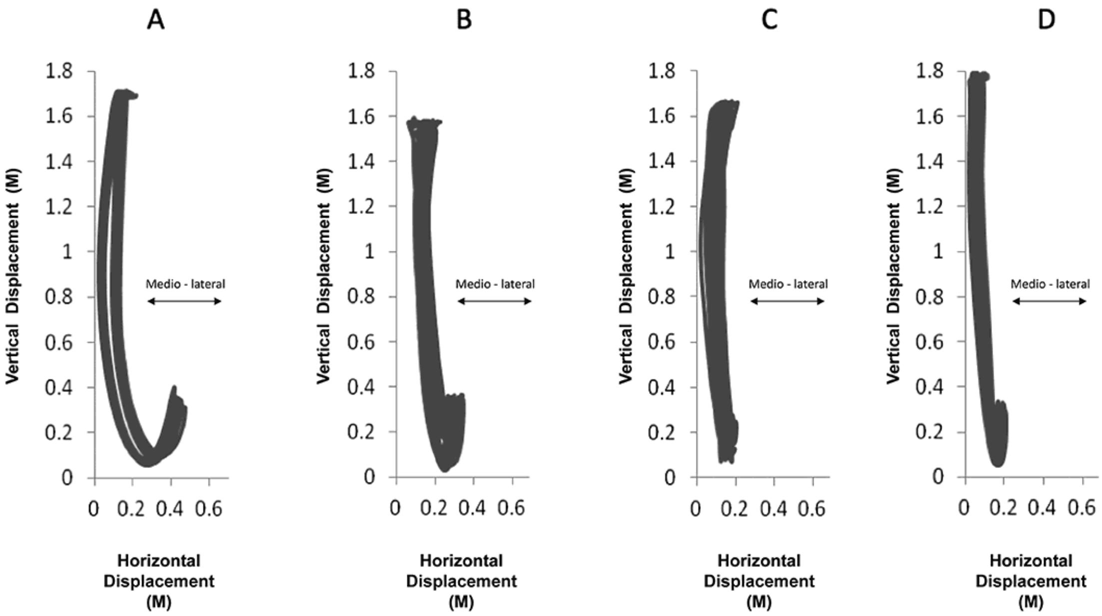

Figure 3.4. Frontal plane kettlebell trajectory

3.4.2 Ratios and Displacement

Table 3.1 illustrates the kettlebell displacement ranges and ratios. The APV and MLV ratios indicate that the C-path followed a larger radius during the upwards than downwards phase for all participants. Participants B, C, and D had a relatively smaller MLV ratio ranging from 0.05-0.13 for both phases compared to participant A, who had a relatively larger MLV ratio of 0.31 ± 0.01 and 0.26 ± 0.02 for the upwards and downwards phases, respectively.

Table 3.1. Mean displacement ranges (m) and ratios for respective participants

	Lifter A		Lifter B		Lifter C		Lifter D	
	Up Phase	Down Phase	Up Phase	Down Phase	Up Phase	Down Phase	Up Phase	Down Phase
APV	0.67 ± 0.02	0.63 ± 0.03	0.66 ± 0.02	0.60 ± 0.02	0.60 ± 0.02	0.56 ± 0.02	0.66 ± 0.02	0.60 ± 0.01
MLR	0.31 ± 0.01	0.26 ± 0.02	0.13 ± 0.03	0.13 ± 0.03	0.05 ± 0.02	0.06 ± 0.02	0.08 ± 0.02	0.07 ± 0.01
Vertical	1.265 ± 0.024	1.265 ± 0.024	1.240 ± 0.020	1.240 ± 0.020	1.393 ± 0.016	1.393 ± 0.016	1.466 ± 0.020	1.466 ± 0.020
AP	0.845 ± 0.014	0.798 ± 0.027	0.820 ± 0.016	0.744 ± 0.025	0.834 ± 0.024	0.783 ± 0.035	0.967 ± 0.014	0.877 ± 0.016
ML	0.394 ± 0.018	0.329 ± 0.031	0.166 ± 0.036	0.165 ± 0.34	0.065 ± 0.026	0.080 ± 0.035	0.113 ± 0.015	0.103 ± 0.015

All data are mean + standard deviations. APV: Anterior-Posterior to Vertical ratio, MLV: Medio-lateral to Vertical ratio.

Table 3.2 shows the AP, ML and vertical displacement ranges between the upwards and downwards phases. The downwards phase represents the smallest arc, compared to the upwards phase. The range between the upwards and downwards phases was largest in the AP, compared to the ML differences in all lifters.

Table 3.2. Three dimensional ranges and effect size between the midpoint of the upwards and downwards phases (m)

	Lifter A	Lifter B	Lifter C	Lifter D
AP	0.049 ± 0.023**	0.076 ± 0.029**	0.046 ± 0.026**	0.090 ± 0.017**
ES	1.99	4.19	2.06	6.67
90% CI	0.038-0.061	0.062-0.089	0.038-0.062	0.083-0.099
ML	0.070 ± 0.020**	0.018 ± 0.013	0.035 ± 0.022	0.014 ± 0.008*
ES	3.30	0.06	0.61	0.59
90% CI	0.06-0.08	0.012-0.024	0.026-0.046	0.004-0.016
Vertical	0.022 ± 0.015**	0.062 ± 0.030**	0.034 ± 0.020	0.094 ± 0.028**
ES	1.29	3.45	0.51	5.34
90% CI	0.014-0.028	0.049-0.076	0.027-0.045	0.082-0.107

All data are mean + standard deviations. AP: Anterior-posterior, ML: Medio-lateral, *Significant difference in positions of upwards and downwards phases ($p < 0.05$),

** Significant difference in positions of upwards and downwards phases ($p < 0.01$).

3.4.3 Velocity

Participants' peak kettlebell resultant velocity ranged from moderate to extremely large ES difference, whereby the upwards phase was faster than the downwards phase for all lifters, except lifter A (see Table 3). Figure 5 shows the typical velocity of the kettlebell as it moved from the downwards phase to the upwards phase. The two peaks in velocity occurred approximately in the re-gripping phase and during the acceleration pull. The two noted times in which velocity reached zero were at fixation, and momentarily between the back and forwards swing.

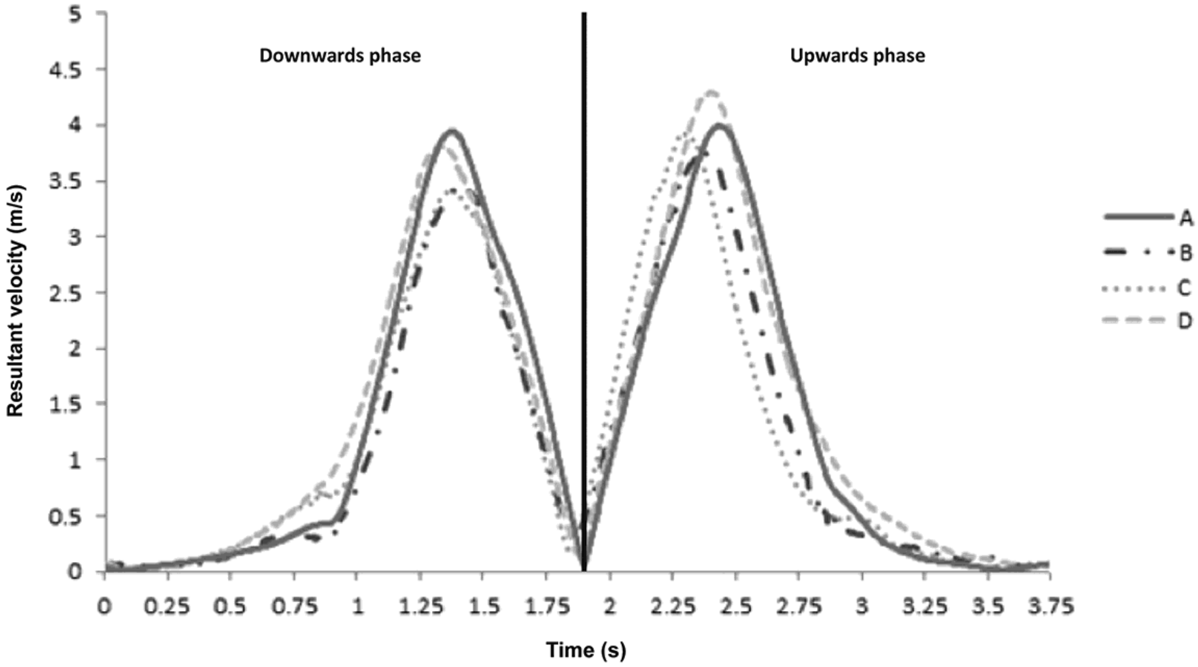

Figure 3.5. Typical kettlebell resultant velocity-time curve for respective participants

Table 3.3. Mean resultant velocity (m.s⁻¹) of respective participants

Phase	Lifter A	Lifter B	Lifter C	Lifter D
Upwards	3.95 ± 0.4	3.88 ± 0.03	4.03 ± 0.13	4.27 ± 0.04
90% CI	3.93-3.97	3.86-3.89	3.99-4.09	4.25-4.29
Downwards	4.00 ± 0.04	3.52 ± 0.05	3.39 ± 0.09	3.83 ± 0.02
ES	1.19**	7.45**	3.21**	12.05**
90% CI	3.98-4.01	3.49-3.54	3.34-3.54	3.82-3.84

All data are mean + standard deviations.

** Significant difference in resultant velocity of upwards and downwards phases ($p < 0.01$).

3.4.4 Movement Variability

Table 3 shows AE, RE and displacement range for the three dimensions for each participant. The AE and the RE indicate that the kettlebell trajectory was highly consistent at each of the four points for all four participants.

Table 3.4. Anterior-posterior displacement range, radial error and absolute error for respective participants (m)

	Lifter A	Lifter B	Lifter C	Lifter D
Phase	Anterior-Posterior			
End Back Swing				
Range	0.054 ± 0.015	0.033 ± 0.012	0.072 ± 0.024	0.044 ± 0.012
AE	0.012 ± 0.09	0.010 ± 0.04	0.019 ± 0.013	0.010 ± 0.007
RE (APV)	0.023 ± 0.016	0.023 ± 0.09	0.024 ± 0.013	0.019 ± 0.012
Acceleration Pull				
Range	0.032 ± 0.009	0.058 ± 0.014	0.066 ± 0.023	0.050 ± 0.011
AE	0.008 ± 0.005	0.010 ± 0.010	0.019 ± 0.013	0.008 ± 0.008
RE (APV)	0.015 ± 0.008	0.017 ± 0.012	0.028 ± 0.014	0.015 ± 0.012
Fixation				
Range	0.039 ± 0.010	0.105 ± 0.028	0.094 ± 0.028	0.067 ± 0.021
AE	0.007 ± 0.006	0.022 ± 0.015	0.022 ± 0.017	0.018 ± 0.010
RE (APV)	0.008 ± 0.006	0.023 ± 0.016	0.023 ± 0.016	0.018 ± 0.010
Re-gripping				
Range	0.105± 0.026	0.069 ± 0.020	0.090 ± 0.023	0.050 ± 0.015
AE	0.016± 0.008	0.016 ± 0.011	0.017 ± 0.015	0.011 ± 0.008
RE (APV)	0.022 ± 0.020	0.024 ± 0.011	0.032 ± 0.027	0.021 ± 0.009

All data are mean + standard deviations. AE: absolute error, RE: radial error, APV: Anterior-Posterior to Vertical ratio, MLV: Medio-lateral to Vertical ratio.

Table 3.5. Medio-lateral displacement range, radial error and absolute error for respective participants (m)

	Lifter A	Lifter B	Lifter C	Lifter D
Phase	Medio-Lateral			
End Back Swing				
Range	0.062 ± 0.016	0.078 ± 0.024	0.051 ± 0.018	0.031 ± 0.009
AE	0.013 ± 0.010	0.019 ± 0.014	0.016 ± 0.007	0.007 ± 0.005
RE (MLV)	0.023 ± 0.016	0.023 ± 0.009	0.024 ± 0.013	0.019 ± 0.012
Acceleration Pull				
Range	0.051 ± 0.017	0.062 ± 0.016	0.056 ± 0.015	0.046 ± 0.012
AE	0.015 ± 0.008	0.015 ± 0.009	0.011± 0.009	0.008 ± 0.009
RE (MLV)	0.015 ± 0.008	0.017 ± 0.012	0.028 ± 0.014	0.015 ± 0.012
Fixation				
Range	0.062 ± 0.020	0.105 ± 0.026	0.090 ± 0.025	0.044 ± 0.014
AE	0.018± 0.009	0.019 ± 0.017	0.019 ± 0.016	0.012 ± 0.008
RE (MLV)	0.018 ± 0.008	0.020 ± 0.016	0.020 ± 0.015	0.012 ± 0.007
Re-gripping				
Range	0.097 ± 0.027	0.073± 0.018	0.108 ± 0.030	0.069 ± 0.019
AE	0.021 ± 0.015	0.014± 0.012	0.024 ± 0.013	0.015 ± 0.011
RE (MLV)	0.025 ± 0.017	0.023 ± 0.012	0.037 ± 0.027	0.023 ± 0.009

All data are mean + standard deviations. AE: absolute error, RE: radial error, APV: Anterior-Posterior to Vertical ratio, MLV: Medio-lateral to Vertical ratio.

Table 3.6. Vertical displacement range, radial error and absolute error for respective participants (m)

	Lifter A	Lifter B	Lifter C	Lifter D
Phase		Vertical		
End Back Swing				
Range	0.093 ± 0.024	0.077 ± 0.022	0.058 ± 0.016	0.074 ± 0.020
AE	0.018 ± 0.015	0.019 ± 0.009	0.012 ± 0.009	0.015 ± 0.011
Acceleration Pull				
Range	0.044 ± 0.014	0.058 ± 0.016	0.069 ± 0.022	0.061 ± 0.016
AE	0.012 ± 0.007	0.011± 0.008	0.018 ± 0.011	0.012 ± 0.011
Fixation				
Range	0.004 ± 0.001	0.018 ± 0.005	0.019 ± 0.005	0.012 ± 0.004
AE	0.001 ± 0.001	0.004 ± 0.003	0.004 ± 0.003	0.003 ± 0.002
Re-gripping				
Range	0.055 ± 0.017	0.071± 0.019	0.144 ± 0.036	0.055 ± 0.018
AE	0.012 ± 0.008	0.015 ± 0.007	0.025± 0.024	0.015 ± 0.009

All data are mean + standard deviations. AE: absolute error, RE: radial error, APV: Anterior-Posterior to Vertical ratio, MLV: Medio-lateral to Vertical ratio.

3.5 Discussion

Three dimensional motion analysis was used in this study to document kettlebell snatch kinematics performed by elite kettlebell athletes. The main findings were that despite some differences between the four athletes, significant commonalities emerged: 1) there was a ‘C’ shape trajectory during the downwards and upwards phases of the snatch; 2) the ‘C’ shape followed a narrower trajectory during the downwards phase; and 3) the resultant velocity time graph resembled an ‘M’ shape.

One marked similarity was the narrow ‘C’ shape trajectory on the way down and a wider ‘C’ shape on the way up. The smaller radius on the way down may be due to several reasons. During the initiation of the downwards phase it was noticed that all athletes moved their bodies away from the kettlebell. This allowed for the kettlebell to remain within the base of support. Following the initial counter movement the athlete flexes and supinates the elbow (Rudnev, 2010; Tikhonov et al., 2009). The supination of the elbow may help to reduce the movement of the kettlebell through the AP plane and minimise grip stress (and subsequent fatigue) during the transition into the re-gripping phase. The flexion of the elbow may also minimise the AP movement of the kettlebell, thereby again placing the kettlebell as close to the base of support as possible. The large radius from the forwards swing to the start of the acceleration pull may help to minimise the centripetal force acting on the grip. Following the acceleration pull, the hand insertion phase guides the kettlebell onto the back of the wrist. The grip must relax during this phase to help facilitate a smooth transition into fixation. Reducing the stress on the grip may help to prolong performance as anecdotally grip endurance is considered the weakest link in elite GS athletes. Paying particular attention to the hand insertion will also help to reduce the potential for the kettlebell to have heavy contact upon the forearm, and therefore reduce the risk of musculoskeletal injury to the distal forearm. Strength and conditioning coaches need to be aware of this before their athletes progress the kettlebell snatch.

Movement was remarkably consistent for all athletes in the frontal and sagittal planes. This is most likely to minimise energy expenditure and therefore fatigue over the ten minute event. The most consistent of the four points was the fixation phase which had a RE range of 0.008

± 0.006 m and 0.023 ± 0.016 m, in both sagittal and frontal planes. This suggests that a consistent fixation phase is of the upmost importance. Low endpoint variability is most useful to ensure that the mass of the kettlebell is over the shoulder in all three planes. If this was not the case, greater energy and time would be used fixating or locking out the kettlebell overhead. Within the limitations of the research it can be concluded that elite kettlebell sport athletes maintain a consistent trajectory, particularly at some of the key positions of the movement. Maintaining consistent fixation may be key in increasing the reproducibility of the trajectory as it marks the start and finish of the lift. The trajectory of the kettlebell for athletes A and C followed a similar path during both the downwards and upwards phases in the sagittal plane, whilst the vertical midpoints were at a relatively similar level for lifters A and C (0.022 ± 0.015 m and 0.034 ± 0.020 m trajectory difference, respectively). In contrast, the trajectory for athletes B and D were visibly separated and the vertical midpoint of the 'C' shape occurred in different vertical positions in the upwards and downwards phases (0.062 ± 0.030 m and 0.094 ± 0.028 m, respectively) (Figure 3.3). These differences in trajectory could be explained by: 1) greater trunk rotation in the acceleration pull phase; 2) the degree of plantar flexion in the upwards or downwards phase; 3) a larger shift backwards during the downwards phase; 4) the position of the upper extremity; and 5) possibly anthropometrical differences. Unfortunately, the present study only assessed the motion of the kettlebell, however, future studies may be useful to better describe the relationship between the kettlebell and lifters kinematics. Potentially, technique may differ over the course of the ten minutes due to fatigue or changes in cadence, however, these differences were beyond the scope of the present study.

Based on the kettlebell kinematics, it appears that different strategies were used to prolong performance in the different lifters. Lifter A displayed the largest MLV range in the upwards and downwards phases, which may produce fatigue in the contralateral musculature to a greater extent. In novice athletes, the mean activation of the lower erector spinae performing the kettlebell snatch with a sagittal plane trajectory was 54.2 ± 18.3 and 61.3 ± 16.3 % MVC for the ipsilateral and contralateral sides, respectively (McGill & Marshall, 2012). Lifter A may increase the demands of the contralateral musculature further by increasing the ML moment arm (which is reflected in his MLV ratio). This may increase the requirements of the torso to resist or control lateral flexion to a greater extent, in an effort to offset fatigue for the last five minutes. In doing so, they may possibly spare the ipsilateral side for subsequent effort following the hand switch as it will become the contralateral side at the five minute mark. Thus, having a larger MLV ratio trajectory may be a strategy to help spread the loading across different muscle groups during the left and right hand efforts. This strategy may be particularly useful during biathlon, as athletes must perform the jerk, which predominantly takes place in the sagittal plane one or two hours prior to the snatch, and may still be experiencing fatigue from this effort (Farrar et al., 2010; Hulsey et al., 2012). Lifters B, C and D had much smaller MLV ratios compared to lifter A. The dominant AP trajectory in lifters B, C and D suggests that their strategy requires relatively symmetrical loading, resulting in less effort by a single muscle group, thus prolonging performance. A sagittal plane dominant trajectory similar to lifters B, C and D may offer strength and conditioning coaches a technique with the greatest ease of application. Conversely, lifter A's style may be useful in a GS setting, however it would require a coach to monitor both sagittal and frontal planes of motion, with respect to the kettlebell trajectory.

As previously stated, upward phase horizontal displacement of the kettlebell was greater than the downward phase equivalent for all lifters, perhaps to reduce the centripetal load on the fingers. Increasing kettlebell velocity may further increase the centripetal stress on the fingers. Two peaks in velocity between the upwards and downwards phases were observed across all lifters. The first peak occurred approximately in the re-gripping phase, and the second generally in the acceleration pull phase. Lifters B, C and D had slower peak velocities in the downwards phase, whereas lifter A's peak velocity was greatest during the downwards phase. Reducing the velocity on the downwards phase could help to reduce stress placed on the finger flexors, however it could also increase the time needed to perform each repetition, which may be counter-productive to the objective of the sport which is to perform as many repetitions as possible in 10 minutes. Strength and conditioning coaches should be aware that in addition to the obvious effect of altering the kettlebell mass, different cadences and/or anthropometric factors may result in different kettlebell velocities. Therefore, an increase in cadence may result in greater velocity in the downwards phase and a faster eccentric phase. This increase in repetition velocity may result in greater grip and systemic fatigue, which may only be sustainable over shorter time periods.

3.5.1 Conclusion

The kettlebell snatch trajectory of elite GS athletes follows a 'C' shaped path. There were two differently shaped 'C' trajectories, one with a smaller radius on the downwards phase, and the other a larger during the upwards phase. Kettlebell displacement occurred predominantly in the sagittal plane, although varying and relatively smaller amounts of horizontal displacement were recorded in the frontal plane. Within the upwards and downwards phases, low movement variability appears an important factor, particularly in the overhead fixation position. With the kettlebells potential large degrees of freedom, individual athlete style may affect their trajectories.

Additionally, there were two peaks in velocity which occurred in the upwards and downwards phases. This technique easily facilitates multiple repetitions due to its cyclical upwards and downwards phases. This research has shown that the kettlebell snatch can be performed with consistent kettlebell trajectories and velocities for 15 repetitions by elite GS athletes in a relatively unfatigued state.

3.5.2 Practical Application

The kettlebell snatch may be a useful addition or alternative to high repetitions of the barbell snatch, as it can be performed consistently. This may be particularly useful for strength and conditioning coaches, wishing to program an explosive total body movement such as the snatch for higher repetitions. Additionally, the unilateral and swinging nature of the kettlebells ‘C’ shaped trajectory and the barbells bilateral ‘S’ shaped trajectory may each provide a unique stimulus. Programming a snatch for higher repetitions may increase the metabolic and grip demands (Beltz et al., 2013). These components may also be important factors in sports that require a combination of strength and endurance qualities. Grip strength is an important component of Judo competition (Miarka et al., 2012). Grappling sports such as Judo, freestyle and Greco-Roman wrestling typically involve tournament formats and a progressive increase in fatigue and grip strength loss occurs with each bout during these tournaments (Barbas et al., 2011; Bonitch-Góngora et al., 2012; Branco et al., 2013; Kraemer et al., 2001). The kettlebell snatch may have potential application in these sports, as it may promote increased levels of local muscular endurance. In contrast, the barbell snatch has been well researched and is an effective stimulus for power adaptations (Garhammer, 1993). Its trajectory follows an ‘S’ shape which is predominantly vertical, allowing for positions which maximise power output. Therefore, the barbell snatch would be most appropriately programmed for lower repetitions, in contrast to the kettlebell snatch, which may be better suited to higher repetitions. The kettlebell snatch has a cyclical component, as it contains an upwards and downwards phase. Following a ‘C’ trajectory will help to prolong performance and in turn training volume, which may allow for greater training outcomes. Problems may arise if a lifter attempted to apply an ‘S’ trajectory to the kettlebell, which may not be appropriate or attainable, and may cause the hand insertion and fixation phases to occur too closely together (when the arm is vertical). This may lead to greater impact upon the forearm, thus increasing the risk of injury. Evidently, kettlebell snatch technique should not be taught in the same manner as the barbell snatch.

3.5.3 Limitations

The small sample size recruited is the major limitation within this research, however the athletes involved are all elite within GS, making them of particular interest. Due to time constraints and international travel stress, the lifters were unable to perform 10 minute sets at a competition pace for this study. This would have offered an insight into their trajectories in a fatigued state. A total of 16 repetitions were studied over one minute. The number of repetitions performed was at competition pace for the two lighter lifters. However, this was below competition pace for the two heavier lifters.

3.5.4 Acknowledgements

The authors would like to thank IKSFA (www.IKSFA.com), WKC (www.worldkettlebellclub.com), Sergey Rudnev and the other athletes for taking part in the research. No financial support was taken from these organizations. We would also like to thank Dr. Brett O’Connell for his technical support.

Chapter 4 - Study 2: External kinetics of the kettlebell snatch in amateur lifters

Statement of publication:

This paper was accepted for publication in the *PeerJ*:

Ross J. A., Wilson C. J., Keogh J. W., and Lorenzen C. 2017. External kinetics of the kettlebell snatch in amateur lifters. PeerJ 5:e3111;DOI 10.7717/peerj.3111, 2017

4.1 Abstract

Background. Kettlebell lifting has gained increased popularity as both a form of resistance training and as a sport, despite the paucity of literature validating its use as a training tool. Kettlebell sport requires participants to complete the kettlebell snatch continuously over prolonged periods of time. Kettlebell sport and weightlifting involve similar exercises, however, their traditional uses suggest they are better suited to training different fitness qualities. This study examined the three dimensional ground reaction force (GRF) and force applied to the kettlebell over a six minute kettlebell snatch set in 12 kettlebell trained males.

Methods. During this set, VICON was used to record the kettlebell trajectory with nine infrared cameras while the GRF of each leg was recorded with a separate AMTI force plate. Over the course of the set, an average of 13.9 ± 3.3 repetitions per minute were performed with a 24 kg kettlebell. Significance was evaluated with a two-way ANOVA and paired t-tests, whilst Cohen's F (ESF) and Cohen's D (ESD) were used to determine the magnitude.

Results. The applied force at the point of maximum acceleration was 814 ± 75 N and 885 ± 86 N for the downwards and upwards phases, respectively. The absolute peak resultant bilateral GRF was 1746 ± 217 N and 1768 ± 242 N for the downwards and upwards phases, respectively. Bilateral GRF of the first and last 14 repetitions was found to be similar, however there was a significant difference in the peak applied force ($F(1.11) = 7.42$, $p = 0.02$, ESF = 0.45). Unilateral GRF was found have a significant difference for the absolute anterior-posterior ($F(1.11) = 885.15$ $p < 0.0001$, ESF = 7.00) and medio-lateral force vectors ($F(1.11) = 5.31$, $p = 0.042$, ESF = 0.67).

Discussion. Over the course of a single repetition there were significant differences in the GRF and applied force at multiple points of the kettlebells trajectory. The kettlebell snatch loaded each leg differently throughout the repetition. Performing the kettlebell snatch for six

minutes resulted in a reduction in peak applied force when the first 14 and last 14 repetitions were compared.

4.2 Introduction

Kettlebell sport, also referred to as Girevoy Sport (GS), competition originated in Eastern Europe in 1948 (Tikhonov et al., 2009). In recent years, kettlebell lifting has gained increased popularity as both a form of resistance training and a sport. The kettlebell snatch is one of the most popular exercises performed with a kettlebell. The movement is an extension of the kettlebell swing, and involves swinging the kettlebell upwards from between the legs until it reaches the overhead position. To date, the barbell snatch has received much attention and reviews of the literature have demonstrated it be an effective exercise for strength and power development (Escamilla, Lander, & Garhammer, 2000; Garhammer, 1993). In contrast, the kettlebell snatch has only just started to receive research attention (Falatic et al., 2015; Lake et al., 2014; McGill & Marshall, 2012; Ross et al., 2015).

In a classic kettlebell competition, the winner is the person who completes the most snatch lifts within a 10 minute period. Current rules stipulate that the athlete can only change the hand holding the kettlebell once during this ten minute period. Additionally, to perform a valid repetition the kettlebell must be locked out motionless overhead at the conclusion of each repetition. The overhead position is known as fixation, which was found to have the lowest movement variability compared to the end of the back swing, and the midpoints of the upwards and downwards phases within its trajectory (Ross et al., 2015). It has been proposed that due to the kettlebell's unique shape and its resulting trajectory, the unilateral kettlebell snatch may be better suited for performing multiple repetitions than a single maximum effort (Ross et al., 2015). Specifically, the kettlebell snatch trajectory follows a 'C' shaped path as it can move in between the athlete's legs (Ross et al., 2015), in contrast to an 'S' shaped trajectory of the barbell snatch (Ho et al., 2014; Newton, 2002), which moves in front of the knees facilitating a double knee bend. In elite kettlebell sport, the kettlebell snatch also involves a downwards phase which follows a smaller radius compared to the kettlebell's upwards phase (Ross et al., 2015). The downwards phase gives the kettlebell snatch more of a cyclical natural than the barbell snatch, where the barbell is dropped from the overhead recovery position, thus providing a training stimulus in both the upwards and downwards phases.

The kettlebell snatch and barbell snatch move through a number of different phases that share some similarities. From the starting position the barbell snatch has the following phases: first pull, transition, second pull and the catch phase (Haff & Triplett, 2015; Ho et al., 2014). In contrast, the kettlebell snatch starts at fixation and has the following phases: drop, re-gripping, back swing, forward swing, acceleration pull and hand insertion phase (Ross et al., 2015; Rudnev, 2010). The second pull has been shown to be the most powerful motion during the barbell snatch (Garhammer, 1993). Similarly, the acceleration pull phase has been suggested to be the most explosive phase of the kettlebell snatch (Rudnev, 2010).

Figure 4.1. illustrates the phases of the kettlebell snatch. A - fixation, B - drop, C - re-gripping, D - back swing, E - forward swing, F - acceleration pull, G- hand insertion, A - fixation.

There is currently little research on the kinetics of the kettlebell snatch. The only study to date recorded the bilateral ground reaction force (GRF) of the kettlebell swing and snatch (Lake et al., 2014). The kettlebell snatch and two handed swing were analysed over three sets of eight repetitions performed with the intention of achieving the maximum velocity possible, with horizontal and vertical work, impulse, mean force and power of the kettlebell snatch and swing calculated (Lake et al., 2014). Both exercises had greater vertical impulse, work, and mean force power than the horizontal equivalent regardless of phase (Lake et al., 2014). The vertical component of the kettlebell snatch and two handed swing were comparable, whilst the two handed swing had a larger amount of work and rate of work performed in the horizontal plane (Lake et al., 2014). One of the limitations was that GRF was investigated bilaterally when the movement is unilateral and is therefore likely to load the ipsilateral and contralateral legs differently (Lauder & Lake, 2008). This study investigated the hardstyle kettlebell snatch, which has a different hip action, when contrasted with the kettlebell sport snatch. The hardstyle kettlebell snatch involves a single explosive leg extension. The upwards phase is described as being a swing, high pull and punch up (Tsatsouline, 2006). In contrast, the kettlebell sport snatch typically involves a double knee bend in an effort to improve the efficiency of the exercise. The double knee bend allows the kettlebell to transition forwards from the end of the back swing, before the explosive leg extension takes place (Rudnev, 2010). Although, there is inter-lifter variation within kettlebell sport technique (Ross et al., 2015), commonly kettlebell sport involves plantarflexion of the ipsilateral ankle during the explosive leg action (see figure 4.2.1), whilst this is not the case within the hardstyle snatch.

This study aims to build on the work by Lake et al (2014) by investigating the unilateral GRF of the kettlebell snatch, throughout key positions of a single repetition and a prolonged set. In addition, force applied to the kettlebell by the lifter was also examined and will further the understanding of the kinetics of the key points of the trajectory outlined previously (Ross et al., 2015). These data will offer coaches an insight into the kinetic demands that the kettlebell snatch places upon the body providing insight to guide kettlebell exercise prescription.

4.3 Methods

4.3.1 Study Design

Twelve amateur kettlebell sport lifters performed six minutes of the kettlebell snatch exercise with one hand change, as is commonly performed in training by GS competitors. GRF was recorded with two AMTI force plates, and kettlebell trajectory was simultaneously recorded with a nine camera VICON Motion Analysis System. The GRF from the force plates allowed us to determine the external mechanical demands applied to the lifter and kettlebell system centre of mass, whilst the inverse kinematics calculated the force applied to the kettlebell. Force was determined using the kettlebell's known mass (kg) and the acceleration ($m.s^{-2}$) determined via inverse kinematics. The aim was to identity the external demands placed upon each leg and the changes in kinetics during a prolonged kettlebell snatch set over six minutes. The dependent variables were: resultant kettlebell force (N), resultant absolute and relative GRF (N) for: resultant, anterior-posterior, medio-lateral and vertical bilateral, GRF impulse (N.s) & resultant velocity of the kettlebell ($m \cdot s^{-1}$). These were measured at the following time points: time of peak GRF, point of maximum kettlebell acceleration, point of maximum kettlebell velocity, end of back swing, lowest kettlebell point, midpoint and highest kettlebell point.

4.3.2 Subjects

Twelve males with a minimum of three years kettlebell training experience (age 34.9 ± 6.6 yr, height 1.8 ± 0.1 m and mass 87.7 ± 11.6 kg, hand grip strength non-dominant 54.5 ± 8.0 kg and dominant 59.6 ± 5.5 kg) gave informed consent to participate in this study. They were free from injury and their training regularly included six minute kettlebell snatch sets. Prior to taking part in the study, the participants performed 6.0 ± 2.1 training sessions per week, of which 3.3 ± 1.9 were with kettlebells. All had previously competed in kettlebell sport and kettlebell sport was the primary sport for nine of the 12 participants. A 24 kg kettlebell was selected, as this is the weight used by 'amateur' lifters within a kettlebell sport competition. This is in contrast to 32 kg weight for 'professional' lifters and 16 kg for 'novice' lifters. The Australian Catholic University's ethics review panel granted approval for this study to take place (ethics number 2012 21V). All participants gave written consent to take part in this research.

4.3.3 Procedures

During a single testing session, athletes performed one six minute kettlebell snatch set with a hand change taking place at the three minute mark. A six minute set was chosen as opposed to the GS standard 10 minute set, as it was attainable for all subjects and is a common training set duration for non-elite kettlebell sport athletes. Hand grip strength was tested with a grip dynamometer with a standardised procedure 10 minutes pre-set and immediately post test (Medicine, 2013). They were provided with chalk and sand paper (as this is standard competition practice) and asked to prepare the kettlebell as they would before training or competition. A range of professional-grade kettlebells of varying masses (Iron Edge, Australia) were available for the lifters to perform their typical warm ups. Following the athletes warm up, each six minute set was performed with a professional-grade 24 kg kettlebell, as is the standard for kettlebell sport within Australia. Three markers were used, one (26.6 mm x 25 mm) was placed on the front plate of the kettlebell, and two markers (14 mm x 12.5 mm in diameter) were placed on the kettlebell at the base of each side of the handle. The markers were placed in these positions to help avoid contact with the lifter during the set. Nine VICON infrared cameras (six MX 13+ & three T20-S) sampling at 250Hz, were placed around two adjacent OR6 AMTI force plates sampling at 1000Hz. The point of origin was set in the middle of the platform, to calibrate the cameras' positions. The athlete was instructed to stand still with one foot on each plate and the kettlebell approximately 20 cm in front of him before the start of the six minute set in order to process a static model calibration. A self-paced set was then performed as if they were being judged in a competition. To initiate the set, the kettlebell was pulled back between the legs.

VICON Nexus software was used to manually label markers, and a frame-by-frame review of each trial was performed to minimise error. Average marker position was computed at rest from initial position. The initial position of the markers was used to compute vectors from centroid to the centre of gravity. Kettlebell motion was computed using singular value decomposition of the marker transformations into a translation, a rotation and an error value (Duarte, 2014). Root mean square error was calculated and time steps with high error values were dropped from analysis. The centre of gravity locations were computed from the translation and rotation of the kettlebell geometry. A third order B-spline was used to interpolate and filter the three dimensional trajectories using the python function ("scipy.interpolate.splprep"). The spline functions ("knots") were then used to compute the velocity and acceleration.

Time steps of the kettlebells trajectory that contained the kettlebell maximum velocity, maximum acceleration (peak resultant kettlebell force) and the following points: end of the back swing, lowest point, midpoints and highest point (overhead lockout position) were identified. At these time steps the resultant kettlebell force, resultant bilateral GRF, and resultant velocity were recorded. Time steps moving from the overhead lockout position to the end of the back swing were allocated a relative negative time in seconds, with the end of the back swing as zero. The time steps from the end of the back swing moving to the overhead lockout were given a positive relative time. Over the entire set at the point that peak bilateral absolute resultant force or peak resultant force for the ipsilateral and contralateral leg was reached, the three dimensional force was reported. In addition to the entire set, the three dimensional bilateral forces were reported for the first and last 14 repetitions. Fourteen repetitions were chosen because it was the closest whole number to the mean repetitions per minute performed by the subjects over the six minutes. The forces were presented in both absolute units and relative to each subject's body mass. As the majority of the work occurred between the end of the back swing and the midpoint of the upwards and downwards phases of its trajectory, absolute and relative impulse for each leg was calculated over this period.

4.3.4 Statistical Analyses

Data were entered into the Statistical Package for the Social Sciences (SPSS), Version 22. The data were screened for normality using frequency tables, box-plots, histograms, z-scores and Shapiro-Wilk tests prior to hypotheses testing. One univariate outlier was detected and removed from three of the data sets, relative unilateral vertical GRF, relative and absolute upwards phase medio-lateral GRF. In order to satisfy normality, the medio-lateral GRF for the absolute upwards phase was transformed using the base 10 logarithm function. Following data screening, the final sample numbered 11 to 12 participants.

A 2x2 two-way ANOVA was used to evaluate the difference within peak resultant kettlebell force, absolute and relative GRF for: resultant, anterior-posterior, medio-lateral and vertical bilateral vectors for both the first and last 14 repetitions and the upwards and downwards phases. Additionally, absolute and relative unilateral GRF vectors were compared with a 2x2 two-way ANOVA between the ipsilateral and contralateral legs as well as the upwards and downwards phases. Temporal measures of kinetics were compared within different points of the kettlebell trajectory with two-tailed paired t-tests and a Bonferroni adjustment. An intra-repetition analysis compared the kinetics at six points of the kettlebell trajectory (highest point, midpoints, lowest points and end of the back swing), additionally peak bilateral GRF, maximum acceleration and peak resultant velocity were compared to their peak value (this was done to determine the different demands throughout a single repetition). The magnitude of the effect or effect size was assessed by Cohen's D (ESD) for t-tests and Cohen's F (ESF) for two-way ANOVA. Trials from both right and left hands were assessed. If the lifter performed an uneven number of repetitions with each hand, the side with the greatest number had repetitions randomly removed in order to allow for an even amount of pairs. Removed repetitions were evenly allocated between each minute. Within each minute, randomly generated numbers corresponding to each were used to determine removed repetitions. The magnitude of the paired t-test effect was considered trivial ESD <0.20, small ESD 0.20-0.59, moderate ESD 0.60-1.19, large ESD 1.20-1.99, very large ESD 2.0-3.99 and extremely large ESD ≥ 4.0 (Hopkins, 2010). Statistical significance for the paired t-tests required $p < 0.001$. The magnitude of difference for the two-way ANOVA was reported as trivial ESF < 0.10, small ESF 0.10-0.24, medium ESF 0.25-0.39 and large ESF ≥ 0.40 (Hopkins, 2003). The two-way ANOVA required $p < 0.05$ for statistical significance.

4.4 Results

A total number of 972 repetitions were analyzed for the twelve amateur kettlebell sport lifters, each performing an average of 13.9 ± 3.3 repetitions per minute. Grip strength of the hand that performed the last three minutes of the set had a reduction ($p= 0.001$, ESD = 0.77) of 9.8 ± 4.4 kg compared to pre-test results. Tables 4.1 and 4.2 show descriptive statistics for the three dimensional GRF and kettlebell force during the first and last 14 repetitions for the absolute and relative values, respectively. The absolute peak resultant kettlebell force was significantly larger for the first repetition period compared to the last [i.e. first 14 vs last 14] when a full repetition was analyzed (i.e. upwards and downwards phases combined) ($F_{(1.11)} = 7.42$, $p = 0.02$, ESF = 0.45).

Table 4.1. Absolute mean (SD) resultant and three dimensional GRF for the first and last 14 repetitions.

	First 14 repetitions		Last 14 repetitions	
	Downwards	Upwards	Downwards	Upwards
GRF (N)	1766 (240)	1775 (277)	1782 (249)	1797 (285)
GRF ML (N)	47 (43)	70 (33)	59 (51)	63 (42)
GRF AP (N)	308 (74)	299 (80)	320 (88)	315 (92)
GRF V (N)	1736 (235)	1746 (271)	1748 (246)	1766 (278)
Resultant peak kettlebell force (N)	809* (74)	895* (76)	826 (85)	879 (101)

ML = medio-lateral, AP = anterior-posterior, V = vertical.
* First 14 repetitions > last repetitions (p = 0.02)

Table 4. 2. Mean (SD) resultant and three dimensional relative GRF (normalised to body weight (N)) for the first and last 14 repetitions.

	First 14 repetitions		Last 14 repetitions	
	Downwards	Upwards	Downwards	Upwards
GRF (BW)	2.06 (0.24)	2.08 (0.31)	2.08 (0.24)	2.10 (0.31)
GRF ML (BW)	0.06 (0.05)	0.08 (0.04)	0.07 (0.06)	0.07 (0.05)
GRF AP (BW)	0.36 (0.08)	0.35 (0.10)	0.37 (0.10)	0.37 (0.11)
GRF V (BW)	2.03 (0.24)	2.04 (0.30)	2.04 (0.25)	2.07 (0.30)

BW = weight body, ML= medio-lateral, AP = anterior-posterior, V = vertical.

Tables 4.3 and 4.4 show the descriptive statistics for the absolute and relative GRF of the ipsilateral and contralateral leg. At the point of peak resultant GRF for either the ipsilateral and contralateral side, a large significant increase was found within the ipsilateral leg in the anterior-posterior vector ($F (1.11) = 885.15$ $p < 0.0001$, ESF = 7.00). In contrast, a large significant increase was found within the contralateral leg of the medio-lateral force vector over a full repetition for both the absolute GRF ($F (1.11) = 5.31$, $p=0.042$, ESF = 0.67) and relative GRF ($F (1.10) = 9.31$, $p=0.01$, ESF = 0.54). No significant differences were found for the absolute and relative impulse of the upwards or downwards phase. Figure 4.2.2 demonstrates a typical three dimensional GRF of the ipsilateral and contralateral side.

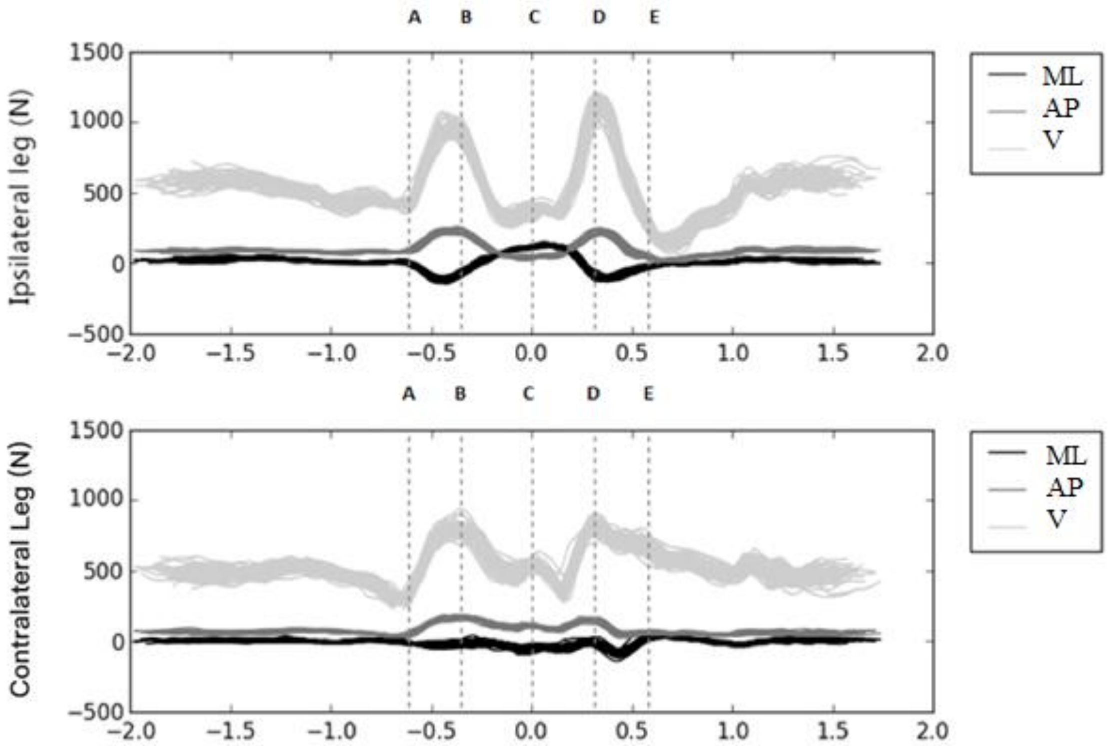

Figure 4.2. Typical three dimensional GRF of the ipsilateral and contralateral legs for an 87 kg athlete. A = Midpoint (down), B = Lowest point (down), C = End of back swing, D = Lowest point (up), E = Midpoint (up), ML= medio-lateral, AP = anterior-posterior, V = vertical.

Table 4.3. Mean (SD) three dimensional forces comparison of ipsilateral and contralateral with values shown as absolute values.

	Ipsilateral Downwards	Contralateral Downwards	Difference	Ipsilateral Upwards	Contralateral Upwards	Difference
GRF (N)	897 (133)	939 (175)	42 4.6%	936 (110)	949 (110)	13 1.38%
GRF ML (N)	34 (16)	59* (56)	25 53.7%	46 (25)	33* (33)	13 32.9%
GRF AP (N)	165 (42)	154 (38)	11 6.9%	164 (39)	146 (42)	18 11.6%
GRF V (N)	885 (126)	939 (166)	54 5.9%	905 (93)	942 (106)	37 4.0%
Resultant Impulse (N·s)	380 (29)	365 (64)	15 4.0%	382 (52)	378 (63)	4 1.0%

ML= medio-lateral, AP = anterior-posterior, V = vertical.
* Contralateral upward and downward phases significantly > ipsilateral upward and downward (p=0.042)

Table 4.4.. Mean (SD) three dimensional forces comparison of relative GRF (normalised to body weight N) ipsilateral and contralateral legs.

	Ipsilateral Downwards	Contralateral Downwards	Difference	Ipsilateral Upwards	Contralateral Upwards	Difference
GRF (BW)	1.07 (0.14)	1.11 (0.15)	0.04 3.7%	1.13 (0.14)	1.11 (0.13)	0.02 1.8%
GRF ML (BW)	0.04 (0.02)	0.08* (0.04)	0.04 66.7%	0.06 (0.04)	0.04* (0.04)	0.02 40.0%
GRF AP (BW)	0.20 (0.05)	0.18 (0.04)	0.02 10.5%	0.20 (0.06)	0.16 (0.03)	0.04 22.2%
GRF V (BW)	1.04 (0.13)	1.07 (0.13)	0.03 2.8%	1.08 (0.19)	1.08 (0.12)	0 0%
Resultant Impulse (BW·s)	0.42 (0.50)	0.44 (0.05)	0.02 4.7%	0.45 (0.05)	0.43 (0.05)	0.02 4.6%

BW = body weight, ML= medio-lateral, AP = anterior-posterior, V = vertical.
* Contralateral upward and downward phases significantly > ipsilateral upward and downward phases (p=0.01)

Tables 4.5 and 4.6 provide data on how the kinematics and kinetics of the kettlebell snatch changed throughout the range of motion. Specifically, these tables list the relative times, resultant velocity and temporal changes in both kettlebell force and GRF with a comparison to their respective peak values during the downwards and upwards phases, respectively. Within the downwards phase there was no significant difference between peak bilateral GRF and bilateral GRF at the point of maximum acceleration, peak resultant velocity and resultant velocity at the midpoint. All other points had significant differences (see tables 4.5 & 4.6).

Table 4.5 Mean (SD) temporal measures of resultant kettlebell force, resultant velocity and resultant GRF of the downwards phase.

	Relative time (s)	Resultant kettlebell force (N)	Resultant velocity (m/s)	Resultant bilateral GRF (N)
Highest point overhead	- 1.72 (0.49)	222 (15)†+	0.28 (0.22)†+	1054 (93)†*
Midpoint	-0.60 (0.04)	284 (53)†+	3.62 (0.21)†‡	866 (153)† +
Peak resultant velocity	-0.53 (0.05)	466 (69)†+	3.81 (0.21)	1139 (165)† *
Maximum acceleration	-0.40 (0.04)	814 (75)	3.23 (0.27)†*	1660 (299)
Peak resultant GRF	-0.34 (0.11)	775 (73)	3.08 (0.29)	1746.68 (217)
Lowest point	-0.31 (0.04)	694 (79)† #	2.69 (0.34)†+	1595 (276)†‡
End of the back swing	0.00 (0.00)	127 (43)†+	0.21 (0.08)†+	940 (169)†+

The effect was trivial unless otherwise stated.
†Significantly (p<0.0001) < Peak value
§Small ESD (0.2-0.6)‡ Moderate ESD (0.6-1.2)
Large ESD (1.2-2.00)
* Very large ESD (2.0-4.0)
+ Extremely large ESD (> 4.00)

Table 4.6. Mean (SD) temporal measures of resultant kettlebell force, resultant velocity and resultant GRF during the upwards phase.

(n=972)	Relative time (s)	Resultant kettlebell force (N)	Resultant velocity (m/s)	Resultant bilateral GRF (N)
End of the back swing	0.00 (0.00)	127 (43)$^{\dagger +}$	0.21 (0.08)$^{\dagger +}$	940 (169)$^{\dagger +}$
Lowest point	0.32 (0.05)	788 (112)$^{\dagger \ddagger}$	2.90 (0.37)$^{\dagger +}$	1701 (320)$^{\dagger \S}$
Peak resultant GRF	0.33 (0.05)	798 (81)$^{\dagger \ddagger}$	2.89 (0.52)$^{\dagger *}$	1768 (242)
Maximum acceleration	0.39 (0.04)	885 (86)	3.51 (0.29)$^{\dagger *}$	1634 (289)$^{\dagger \S}$
Peak resultant velocity	0.51 (0.05)	596 (62)$^{\dagger *}$	4.16 (0.23)	1095 (164)$^{\dagger *}$
Midpoint	0.60 (0.04)	314 (38)$^{\dagger +}$	3.82 (0.20)$^{\dagger \#}$	838 (122)$^{\dagger +}$

The effect was trivial unless otherwise stated.
†Significantly ($p<0.0001$) < Peak value
§Small ESD (0.2-0.6)
‡ Moderate ESD (0.6-1.2)
$^{\#}$ Large ESD (1.2-2.00)
* Very large ESD (2.0-4.0)
$^{+}$ Extremely large ESD (> 4.00)

4.5 Discussion

Three dimensional motion analysis was used in this study to document kettlebell snatch kinetics of trained kettlebell sport athletes over a six-minute period. The main finding of this study was that the bilateral GRF was similar from the first and the last 14 repetitions, however, there were large significant differences within the resultant kettlebell force of the first and last 14 repetitions. Large differences were found between the ipsilateral and contralateral leg GRF within the anterior-posterior and medio-lateral vectors. Over the course of a single repetition, large differences in kettlebell force and GRF were evident as the kettlebell moved from the end of the back swing, to the lowest point, midpoint and highest point in the upwards and downwards phases. There were large differences in the bilateral GRF and the kettlebell force across different parts of the range of motion.

The kettlebell swing has received more attention than the kettlebell snatch in the scientific literature, possibly due to the relative ease of teaching and learning of the swing compared to the snatch. The kettlebell swing has been found to be an effective exercise for improving jump ability (Jay et al., 2013; Lake & Lauder, 2012a, 2012b; Otto III et al., 2012), strength (Beltz et al., 2013; Lake & Lauder, 2012a, 2012b; Manocchia et al., 2010; Otto III et al., 2012) and aerobic fitness (Beltz et al., 2013; Falatic et al., 2015; Farrar et al., 2010; Hulsey et al., 2012; Thomas et al., 2013). Additionally, the kettlebell swing was suggested to be a useful exercise for improving sprinter performance as it has a higher ratio of horizontal to vertical GRF compared to squat variations (Beardsley & Contreras, 2014). Previous research involving the (one armed) kettlebell snatch found the bilateral mechanical demands were similar to that reported for the two handed kettlebell swing in several ways (Lake et al., 2014). For example, both exercises have a net vertical impulse greater than the net horizontal impulse (Lake et al., 2014). Further, the marked difference between peak vertical and anterior-posterior GRF of the kettlebell snatch within this study support this. There appears to be little difference in the magnitude of the vertical impulse of the two kettlebell exercises, however, the horizontal impulse appears larger for the swing (Lake et al., 2014). It is acknowledged that the two handed kettlebell swing may be a more accessible choice for lower body power and strength training than the kettlebell snatch. However, the unilateral nature of the kettlebell snatch results in a different three dimensional kinetic profile and may provide greater rotational core stability demands than the two handed kettlebell swing. Muscle activation of the contralateral upper erector spinae has been shown to be higher than the ipsilateral portion of this muscle group during the one armed swing and the same side during the two armed swing (Andersen et al., 2015). Further, results of the current study indicated that the kettlebell snatch produced large effect size differences in two of the GRF vectors between the two legs. This suggests that the rotational component imposed different unilateral and force vector demands upon the entire body. The peak resultant force of the ipsilateral leg was found to occur later than the contralateral leg which has also been shown in the unilateral dumbbell snatch (Lauder & Lake, 2008). This suggests that during whole body exercises, holding the implement in one hand will place somewhat different demands, albeit of a modest magnitude, on the lower body even when it is functioning bilaterally.

This study demonstrates that with training, experienced kettlebell athletes are able to sustain consistent GRF over a prolonged six-minute set of kettlebell snatch, even though the kettlebell force over different points of the trajectory exhibited marked differences within each repetition. Interestingly, the peak resultant kettlebell force of the first 14 repetitions was significantly greater than the last 14 repetitions, suggesting that the kettlebell athletes were becoming fatigued at the end of the six minutes. This may be explained by the reduced hand grip strength that we observed, which anecdotally may be a limiting factor within kettlebell snatch competitions. The kettlebell athlete may attempt to take advantage of the less demanding phases of the kettlebell snatch to rest their grip, so as to prolong their performance.

Within different phases of the kettlebell snatch there were marked differences in the intra-repetition kinetics. The differences in the kettlebell force throughout the range of motion may be an indicator of an efficient technique, thereby enabling prolonged performance of the kettlebell snatch. Peak resultant acceleration (in the upwards phase) occurred slightly after the lowest point of the trajectory, approximately after the kettlebell passed the knees. At the midpoint of the trajectory, the GRF of the upwards (838 ± 122 N) and the downwards phases (866 ± 153 N) was similar in magnitude to the body mass of the subjects (860 ± 113 N). The low GRF in the overhead position suggests that the bulk of the lower body's workload takes place as the kettlebell moves from the midpoint to the end of the back swing and back to the midpoint of the kettlebell snatch. The midpoint of the snatch is similar to a swing end point, as the swing follows the same trajectory and is analogous to the barbell snatch pull within weightlifting. Interestingly, the end of the back swing for the kettlebell snatch has the lowest kettlebell force of 121 ± 45 N, which is approximately half the weight force (235 N) of the 24 kg kettlebells. It has been suggested that this is one of two points (along with the overhead fixation position) of relative relaxation in the kettlebell snatch (McGill & Marshall, 2012). In fixation, the arm is positioned overhead with the kettlebell resting on the back of the distal forearm, with the handle sitting diagonally across the palm. This position has been shown to exhibit low variability in elite kettlebell sport lifters (Ross et al., 2015). This low variability may promote metabolic efficiency and safety by reducing the muscular effort required to hold the kettlebell overhead, additionally it is necessary to perform a valid repetition within kettlebell sport. Comparatively, this may not be applicable to hardstyle kettlebell snatch technique, as this style has a focus on effectiveness, rather than efficiency and does not generally involve determining valid repetitions. Following the point of relaxation at the end of the back swing, the forward swing transitions the kettlebell past the knees where the acceleration pull occurs. The acceleration pull is the most explosive movement of the kettlebell snatch and serves a similar function to the second pull in weightlifting. Resultant maximum acceleration occurred slightly after the lowest point suggesting it starts as the kettlebell passes the knees during the forwards swing of the snatch. Peak barbell velocity marks the end of the second pull phase within the barbell snatch (Ho et al., 2014), which suggests that the point of peak resultant velocity marks the end of the acceleration pull phase. Peak resultant velocity occurs just before the midpoint of the upwards phase. The kettlebells backwards and forwards swing in the snatch is somewhat similar to the first pull and transition phase in the weightlifting pull. As the kettlebell swings forward it is progressively accelerated, until peak acceleration when the body of the lifter is in a more advantageous position. By having peak acceleration as the kettlebell passes the knees, force may be applied more efficiently, much like the power position in the weightlifting pull (Newton, 2002). The changes in the force applied to the kettlebell during its trajectory have been found to occur in conjunction with sequential muscular contraction and relaxation cycles (McGill & Marshall, 2012). In addition to these rapid contraction–relaxation cycles, kettlebell sport athletes use the lockout or fixation position to briefly rest between repetitions. Controlling the kettlebell overhead allows a valid repetition, but it will also enable the athlete to regulate their pace, with longer and shorter pauses facilitating a slower or faster pace, respectively.

4.5.1 Conclusion

In summary, the GRF and force applied to the kettlebell changes during different stages of the kettlebell snatch. Additionally, the kettlebell snatch places different external demands upon the ipsilateral and contralateral legs within the AP and ML force vectors. Thus, despite the kettlebell snatch being performed with two legs, each leg may be loaded differently, thereby offering a different stimulus to each leg. There are rapid changes within the kinetics during different phases of the lift. In the upwards and downwards phases there were extremely large significant intra-repetition differences within GRF, kettlebell velocity and force applied to the kettlebell. Applied force to the kettlebell during the first and last 14 repetitions at the point of peak resultant kettlebell force is altered over the course of a prolonged set, possibly due to muscular fatigue, which is further supported by a marked reduction in hand grip strength. The data from this investigation suggest that the kettlebell snatch may provide a unique training stimulus, compared to other exercises (e.g. barbell snatch), as it has a downwards phase and places different demands upon the ipsilateral and contralateral legs. In addition, within their respective sports the barbell and kettlebell snatches sit on different ends of the strength-endurance continuum.

4.6 Acknowledgments

The authors would like to thank Angus McCowan for his assistance in the data analysis.

Chapter 5 - Discussion

Many fitness professionals use the kettlebell snatch in their training programs to improve strength and muscular power and endurance, despite a paucity of scientific support for the exercise. This program of research was undertaken to further scientific understanding of the kinematics and kinetics of the kettlebell snatch. The aim of study one was to document the kettlebells trajectory and its variability during the kettlebell snatch exercise when performed by elite level lifters. The primary findings of this study were that the kettlebell trajectory followed a 'C' shape and that there was low end point variability. Following this, study two investigated the external kinetics of the kettlebell snatch, specifically the GRF and the force applied to the kettlebell over a six minute set. In this study, extremely large intra-repetition differences in force applied to the kettlebell and GRF were found. Additionally, the mean peak kettlebell force of the last 14 compared to the first 14 repetitions of the kettlebell snatch was significantly reduced. The drop in peak kettlebell force corresponded with reduced grip strength immediately post exercise. This chapter will discuss how these findings could be applied practically in a training setting.

The kettlebell snatch has a cyclical nature with both an upwards and downwards phase. As previously stated, the trajectory of the kettlebell snatch was found to be a 'C' shape, although the downwards phase displayed a narrower radius compared to the upwards phase. The narrower trajectory during the downwards phase may have been due to the counter movement of the body that took place during the descent as the kettlebell moved forwards and downwards. Despite the differences within the kinematics of the upwards and downwards phases there were no significant differences within the bilateral peak GRF or impulse. The larger radius of the upwards phase may have helped to prolong performance by reducing the centripetal force or force applied to the kettlebell. If the radius was smaller, the kettlebell force of the upwards phase may have been increased, and subsequently increased forearm fatigue. Not surprisingly, the upwards phase had the largest kettlebell force at the point of maximum acceleration.

The kettlebell snatch is considered to be a ballistic exercise with rapid acceleration, which moves the kettlebell primarily vertically with some motion also occurring in the anterior-posterior and medio-lateral planes. Rapid changes within the intra-repetition external kinetics were one of the major findings of the second study within this research program. Athletes taking part in kettlebell sport use the overhead lockout position to rest and pace themselves, which was evident by the reduced kettlebell force and GRF's recorded in these positions. Additionally, the end of the back swing is considered by GS coaches to offer a brief period of rest. The mean kettlebell force at the end of the back swing was significantly less with an extremely large effect size compared to the point of maximum acceleration, suggesting that there are relatively less demands placed upon the grip at this position. This would support the coaches suggestions that the end of the back swing offers a moment of rest. The maximum point of acceleration during the forward swing phase and most demanding point upon the grip occur 0.39 (0.04) seconds after the end of the back swing. From a coach's perspective this would be just after the kettlebell passes through the knees. The midpoint of the kettlebells trajectory occurred 0.60 (0.04) seconds after the end of the back swing, also with an extremely large significant difference within peak kettlebell force. As such, once the arm holding the kettlebell passes parallel to the ground the lifter will just glide the kettlebell to the overhead position. Further, there were extremely large significant differences in the intra-repetition GRF compared to their peak values, supporting previous findings of rapid changes of myoelectrical activity during each repetition (McGill & Marshall, 2012).

Girevoy sport athletes adopt techniques that will allow them to prolong performance. Rapid changes within the intra-repetitions kinetics may allow them to rest and pace themselves at different positions. The external kinetics of the upwards and downwards phase had no significant differences, however there were large significant differences between the mean kettlebell force of the first compared to last 14 repetitions. The changes to peak kettlebell force were possibly due to athlete fatigue. Grip fatigue is anecdotally the most immediate limiting factor to performance and this was supported by our data. Grip strength significantly decreased at the end of the six minutes while there was no significant reduction within the three dimensional GRF, suggesting that the lower body wasn't significantly affected. Large significant differences within the AP ($F(1.11) = 885.15$ $p < 0.0001$, ESF = 7.00) and the ML ($F(1.11) = 5.31$, $p=0.042$, ESF = 0.067) unilateral force vectors were found. A trajectory with increased displacement range within the frontal plane may increase the ML GRF. Increasing the ML displacement range may be a strategy to shift the load further to the contralateral musculature, thus sparing the ipsilateral musculature. Unpublished GRF data from our first study with elite subjects suggests that the athletes could use a bilateral style or an asynchronous style. Each style could be specific to the individuals upwards and downwards phase. The bilateral style is characterised by an increase in GRF within both legs, whilst the asynchronous style involves simultaneous unilateral increases and decreases within GRF. The bilateral style may help to prolong performance by reducing peak force placed upon each leg, whilst the asynchronous style may require more from one leg and spare the other. The asynchronous style involves large shifts within the body, allowing for one leg to function as the 'power' leg and the other to function as a supporting leg.

The kettlebell snatch involves several key movement patterns, namely: a lower body pull, upper body pull, rotation of the trunk and hip. In contrast, the barbell snatch consists of a lower body pull, upper body pull and a squat. The barbell snatch involves a more efficient vertical trajectory, whilst the kettlebell snatch has relatively greater contributions within its kinematics from the other planes of motion. If specific training is found to be an important component of exercise transference then the kettlebell snatch may have use within sports that involve other planes of motion.

5.1.1 Limitations

Within our first study there were several limitations. Firstly, data was collected from only four elite GS athletes. It is hard to generalise with such a small sample, additionally as world champions they may possess unique attributes. Secondly, data was only collected for the first minute. Thirdly, we only placed markers on the kettlebell, which only offers us an insight into the trajectory of the kettlebell, not joint kinematics. As time was limited with the athletes, it was not feasible to collect joint data.

Within the second study there was only one hand change and we have shown that within trained athletes there is a reduction in peak kettlebell force, which may in turn change the kinematics in addition to the kinetics. The second study was performed on trained subjects who trained 6.0 ± 2.1 per week and 3.3 ± 1.9 of these were with kettlebells, however, they were not elite, consequently, the participants may not have been the best representation of kettlebell lifting technique. All the subjects had at least three years of kettlebell training experience, however there were a range of abilities due to the different frequency of kettlebell specific training and there were a large range of body weights. Additionally, we only collected data for the external kinetics.

4.1.2 Conclusion

In conclusion, the trajectory of the kettlebell snatch follows a ‘C’ shape with a narrow radius in the downward phase. The back swing component of the ‘C’ shape allows the lifter to use the potential energy from the upswing. Over the course of a six minute continuous set, the force applied to the kettlebell and grip strength significantly decrease, whilst GRF has no significant difference. There is both inter and intra variability within the kettlebell trajectory. Elite GS athletes use a trajectory that is predominantly in the sagittal plane, however the kettlebell snatch is performed unilaterally. As such, it has a larger degree of freedom compared to the bilateral barbell snatch. One of the elite GS athletes tested utilized the frontal plane to a greater extent, suggesting there is a large scope for inter lifter variability. There are also different demands that are placed upon the ipsilateral and contralateral sides. The ipsilateral and contralateral sides had larger significant differences within the AP and ML force vectors. As such, the kettlebell snatch may offer a useful training option for strength and conditioning coaches.

4.1.3 Future Research Directions

Kettlebell training is gaining popularity as a mode of resistance training and metabolic conditioning, yet key areas need to be investigated to elucidate the benefits of this type of exercise. Firstly, there have been two studies reporting the external kinetics of the kettlebell snatch, thus a study analysing the internal kinetics and kinematics would be useful. Following this, an intervention to determine how the kettlebell snatch may transfer to other fitness qualities/activities would offer an insight into prescription.

Chapter 5 – References

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Appendix i: Ethics approvals, letters to participants and consent forms

Study 1: Letter to participants and consent forms

ACU Human Ethics Committee Approval Number: 2012 21V

Information Letter to Participants

TITLE OF PROJECT: Biomechanical analysis of the kettlebell snatch

PRINCIPAL SUPERVISOR: Dr Christian Lorenzen

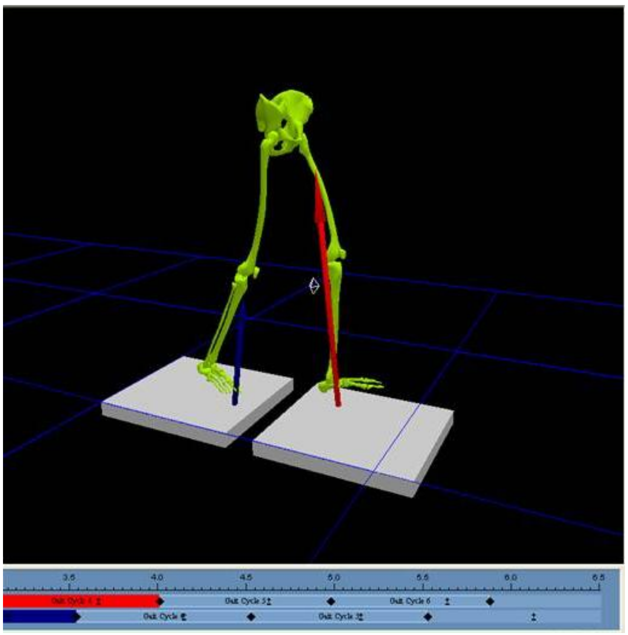
STUDENT RESEARCHER: James Ross

PROGRAMME IN WHICH ENROLLED: Masters Degree by Research
Dear Participant,

You are invited to participate in a study investigating the snatch technique of elite kettlebell lifters. The knowledge gained from this study will give coaches and athletes a better understanding of the techniques used by elite kettlebell athletes.

The possible risks and discomfort to you are negligible and will not be beyond those you experienced during your normal training. A possible inconvenience will be the requirement of attending a two hour testing session at the Australian Catholic University, Fitzroy.

At this session, your snatch technique will be analysed over a 6-10 minute period using three-dimensional camera's and force platforms. Over the two hour period, reflective markers will be placed upon you hip, knee and ankle joints. The cameras will measure your joint angles during the snatch from these markers. The camera system will not record actual images of you, but will look some like the diagram below.



The findings of this research may help you and/or your coaches improve your training and preparation for competition by having a better understanding of your technique, and that of other elite lifters. Furthermore, it is our intention to present the findings of the group data in the form of a journal publication. This means other athletes within the community will be able to benefit from the knowledge gained from this study. Please note that you will not be named within this report and no one outside of you and the team of researchers will be able to identify your results at any time during or following the testing. An identification number will be assigned to your data, known to only the researchers.

Be advised that as a participant you are free to refuse consent altogether without having to justify that decision, and if you wish to, can withdraw consent and discontinue participation in the study at any time without giving a reason. Withdrawal from the research study will not impact upon your employment or team selection.

Should you have any questions regarding this project, please contact the Principal Supervisor:

Dr Christian Lorenzen
(03) 9953 3849
School of Exercise Science
ACU National, St Patrick's Campus, 115 Victoria Parade, Fitzroy, VIC 3065

On completion of the study, we would be delighted to discuss with you the findings of the study, and your individual results. Before deciding to take part in this study, it is important for you to be aware that this study has gained approval by the Human Research Ethics Committee at Australian Catholic University. This vigorous process ensures that the study is worthwhile and protects you the participant.

In the event that you have any complaint or concern about the way you have been treated during the study, or if you have any query that the Investigators have not been able to satisfy, you may write to the Chair of the Human Research Ethics Committee care of the Victorian Research Services Unit.

Chair, HREC
C/o Research Services
Australian Catholic University
Melbourne Campus
Locked Bag 4115
FITZROY VIC 3065
Tel: 03 9953 3158 Fax: 03 9953 3315

Any complaint or concern will be treated in confidence and fully investigated. The participant will be informed of the outcome.

If you agree to participate in this project, you should sign both copies of the Consent Form. Please retain one copy for your records and return the other copy to the Principal Supervisor or Student Researcher.

Dr Christian Lorenzen	James Ross
Principal Supervisor	Student Researcher

CONSENT FORM
Copy for Researcher / Copy for Participant to Keep

TITLE OF PROJECT: Movement analysis of the kettlebell snatch.

PRINCIPAL SUPERVISOR: Dr. Christian Lorenzen

STUDENT RESEARCHER: James Ross

I .... *(the participant)* have read (*or, where appropriate, have had read to me)* and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this project that will consist of a single, 2 hour testing session. I understand that I will be performing 6-10 minutes of submaximal snatch exercise that will be analysed with 3-dimensional cameras, and my image will not be identifiable from the camera recordings. I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT: ....

SIGNATURE .... DATE ....

SIGNATURE OF PRINCIPAL SUPERVISOR:...

DATE:………………………..

SIGNATURE OF STUDENT RESEARCHER: ....

DATE:........................…
…….

Study 2: Letter to participants and consent forms
ACU Human Ethics Committee Approval Number: 2012 21V

Information Letter to Participants

TITLE OF PROJECT: Biomechanical analysis of the kettlebell snatch

PRINCIPAL SUPERVISOR: Dr Christian Lorenzen

STUDENT RESEARCHER: James Ross

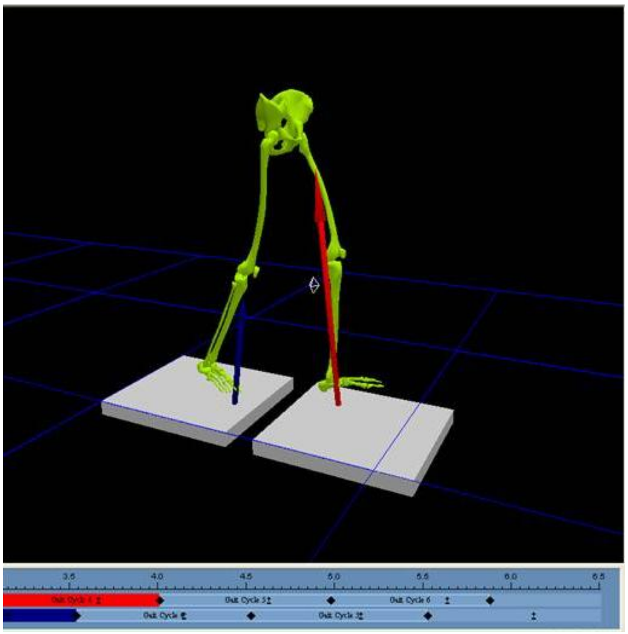
PROGRAMME IN WHICH ENROLLED: Master Degree by Research

Dear Participant,

You are invited to participate in a study investigating the snatch and jerk technique of elite and trained kettlebell lifters. The knowledge gained from this study will give coaches and athletes a better understanding of the techniques used by elite kettlebell athletes.

The possible risks and discomfort to you are negligible and will not be beyond those you experienced during your normal training. A possible inconvenience will be the requirement of attending a two hour testing session at the Australian Catholic University.

At this session, your snatch technique will be analysed over a 6-10 minute period using three-dimensional cameras and force platforms. Your jerk technique will be analysed as part of the warm up. Over the two hour period, reflective markers will be placed upon you hip, knee and ankle joints. The cameras will measure your joint angles during the snatch from these markers. The camera system will not record actual images of you, but will look something like the diagram below.



The findings of this research may help you and/or your coaches improve your training and preparation for competition by having a better understanding of your technique, and that of other elite lifters. Furthermore, it is our intention to present the findings of the group data in the form of a journal publication. This means other athletes within the community will be able to benefit from the knowledge gained from this study. Please note that you will not be named within this report and no one outside of you and the team of researchers will be able to identify your results at any time during or following the testing. An identification number will be assigned to your data, known to only the researchers.

Be advised that as a participant you are free to refuse consent altogether without having to justify that decision, and if you wish to, can withdraw consent and discontinue participation in the study at any time without giving a reason. Withdrawal from the research study will not impact upon your employment or team selection.

Should you have any questions regarding this project, please contact the Principal Supervisor:

Dr Christian Lorenzen
(03) 9953 3849
School of Exercise Science
ACU National, St Patrick's Campus, 115 Victoria Parade, Fitzroy, VIC 3065

On completion of the study, we would be delighted to discuss with you the findings of the study, and your individual results.

Before deciding to take part in this study, it is important for you to be aware that this study has gained approval by the Human Research Ethics Committee at Australian Catholic University. This vigorous process ensures that the study is worthwhile and protects you the participant.

In the event that you have any complaint or concern about the way you have been treated during the study, or if you have any query that the Investigators have not been able to satisfy, you may write to the Chair of the Human Research Ethics Committee care of the Victorian Research Services Unit.

Chair, HREC
C/o Research Services
Australian Catholic University
Melbourne Campus
Locked Bag 4115
FITZROY VIC 3065
Tel: 03 9953 3158 Fax: 03 9953 3315

Any complaint or concern will be treated in confidence and fully investigated. The participant will be informed of the outcome.

If you agree to participate in this project, you should sign both copies of the Consent Form. Please retain one copy for your records and return the other copy to the Principal Supervisor or Student Researcher.

Dr Christian Lorenzen	James Ross
Principal Supervisor	Student Researcher

Consent Form

Copy for Researcher / Copy for Participant to Keep

TITLE OF PROJECT: Movement analysis of the kettlebell snatch.

PRINCIPAL SUPERVISOR: Dr. Christian Lorenzen

STUDENT RESEARCHER: James Ross

I .... *(the participant)* have read (*or, where appropriate, have had read to me)* and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in this project that will consist of a single, 2 hour testing session. I understand that I will be performing 6 minutes of submaximal snatch exercise that will be analysed with 3-dimensional cameras, and my image will not be identifiable from the camera recordings. I realise that I can withdraw my consent at any time without adverse consequences. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT: ....

SIGNATURE .... DATE

....

SIGNATURE OF PRINCIPAL SUPERVISOR:..

DATE:………………………..

SIGNATURE OF STUDENT RESEARCHER: ....

DATE:.....................……….

Australian Catholic University Limited, ABN 15 050 192 660
Fitzroy Campus, 115 Victoria Parade, Fitzroy, VIC 3065 Australia
Locked Bag 4115, Fitzroy, VIC 3065 Australia
CRICOS registered provider: 00004G, 00112C, 00873F, 00885B

Appendix ii: Study 1 Publication

Snatch Trajectory of Elite Level Girevoy (Kettlebell) Sport Athletes and its Implications to Strength and Conditioning Coaching

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[4]Cluster for Health Improvement, Faculty of Science, Health, Education and Engineering, University of the Sunshine Coast

ABSTRACT

Girevoy sport (GS) has developed only recently in the West, resulting in a paucity of English scientific literature available. The aim was to document kettlebell trajectory of GS athletes performing the kettlebell snatch. Four elite GS athletes (age = 29-47 years, body mass = 68.3-108.1 kg, height 1.72-1.89 m) completed one set of 16 repetitions with a 32.1 kg kettlebell. Trajectory was captured with the VICON motion analysis system (250 Hz) and analysed with VICON Nexus (1.7.1). The kettlebell followed a 'C' shape trajectory in the sagittal plane. Mean peak velocity in the upwards phase was 4.03 ± 0.20 m s^{-1}, compared to 3.70 ± 0.30 m s^{-1} during the downwards phase, and mean radial error across the sagittal and frontal planes was 0.022 ± 0.006 m. Low error in the movement suggests consistent trajectory is important to reduce extraneous movement and improve efficiency. While the kettlebell snatch and swing both require large anterior-posterior motion, the snatch requires the kettlebell to be held stationary overhead. Therefore, a different coaching application is required to that of a barbell snatch.

Key words: Kettleball Snatch, Kinematics, Local Muscular Endurance, Motion Analysis

Reviewers: Jason Lake (University of Chichester, UK)
Harvey Newton (Newton Sports, USA)

INTRODUCTION

Kettlebell exercise was initially seen at the end of the 17th century in Russia, where strongmen used 16 kg, 32 kg and 48 kg kettlebells to demonstrate feats of strength at fairs, festivals and circuses [1, 2]. The first kettlebell sport, or 'Girevoy sport' (GS) competition was held in 1948 and fourteen years later, GS was included into the national sports of Russia [1]. Over the past ten years, kettlebell training has become increasingly popular as a form of resistance training for athletes and members of the general population, coinciding with increased participation in GS competition. While the versatility of kettlebells allows the performance of many exercises; swings, jerks, clean and jerks, and snatches are some of the most commonly performed kettlebell movements.

The snatch is typically performed with a barbell in Olympic weightlifting events, although dumbbell and kettlebell versions are becoming more popular. The kettlebell snatch is performed in a biathlon or as a standalone event in GS competitions. The competition takes place on a weightlifting platform and has a time limit of ten minutes per set. The biathlon is scored as the total number of repetitions performed from two exercises: the jerk followed by the snatch, each of ten minutes duration, with at least an hour between exercises. The snatch is performed with one hand change permitted per set and is considered the most technical event in GS [1]. Elite individuals perform the kettlebell snatch with a 32 kg kettlebell during the ten minute competition, with the current absolute world record standing at 238 snatches.

It has been suggested that kettlebell training is a useful mode of training to improve aerobic fitness [3-5],vertical jump [6-9] and back squat performance [7, 9]. Previous research utilising a 32 kg 2-handed kettlebell swing demonstrated similar power outputs and a larger impulse, compared to the jump squat with 40% 1RM [8]. A training study comparing the chronic effects of kettlebell swings and jump squats was reported to significantly improve vertical jump and back squat 1RM. However, the kettlebell group had a smaller improvement in the vertical jump, yet larger improvement in back squat performance [7]. Of the two interventions that investigated the effects of kettlebell training on the cardiorespiratory system, only one found improvements. It is possible that the reason for the lack of improvement was due to the low training dosage of 10-15 minutes three times a week with 70% adherence [10]. In contrast, 30-45 minutes of training twice a week, using a combination of kettlebell exercises including the snatch, was found to improve $\dot{V}O_2$ peak by 13.8% during a progressive kettlebell snatch set [5].

Generally, only qualitative descriptions of the kettlebell snatch during elite performance are available. The International Kettlebell Sport & Fitness Academy has described the snatch as comprising six components [11]. As seen in Figure 1, the start and finish are referred to as "fixation". This is where the kettlebell is locked out overhead. The three components of the downwards phase include: the drop, re-gripping, and back swing, while the upwards phase involves the forward swing, acceleration pull, and hand insertion (refer to Figure 1).

Figure 2, point 1 represents fixation. In this position, the handle of the kettlebell rests diagonally across the palm and the ball rests on the back of the wrist and forearm [11]. The drop is initiated by a counter movement of the torso away from the kettlebell. At approximately the same time, the shoulder begins to extend, and the elbow supinates and flexes [1, 11]. Between the 'drop' and the 'back swing' the handle is repositioned (re-gripped) from the palm to the fingers [11]. This portion of the downwards trajectory is indicated at approximately Figure 2, point 2. At the start of the back swing the knees are slightly flexed and the torso remains upright, until the kettlebell passes between the legs, whereby the hips flex and the knees extend (finishing at Figure 2, point 3). The forwards swing phase consists of the kettlebell moving forward between the legs via hip extension and

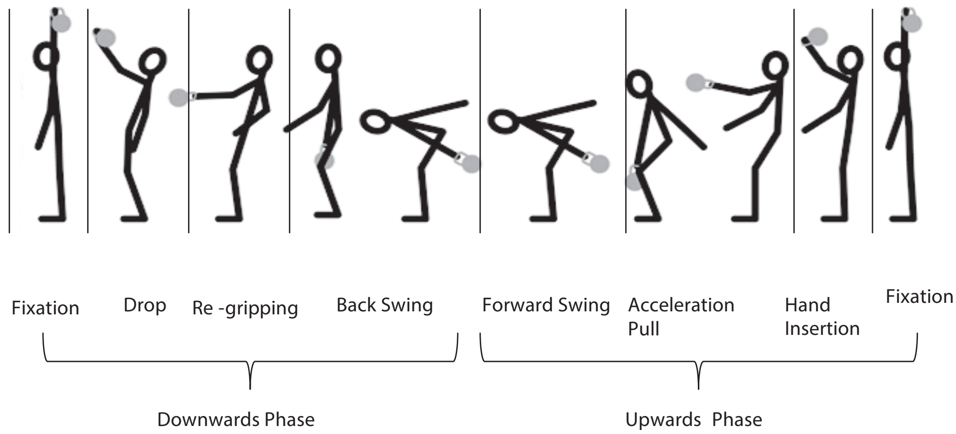

Figure 1. Phases of the Kettlebell snatch

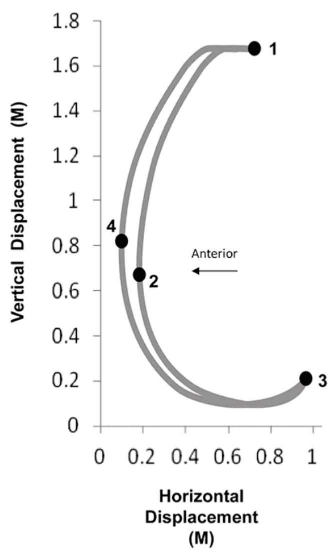

Figure 2. An example of the four points of error in the Kettlebell snatch

knee flexion. The acceleration pull (approximately Figure 2, point 4) begins as the kettlebell passes the knees. This is the most powerful motion in the snatch, and involves knee and hip extension, ipsilateral torso rotation and elbow flexion [11]. It ends when the kettlebell is once again re-gripped (hand insertion). During the hand insertion phase, the elbow is extended and the torso rotates contralaterally [11]. This rotates the kettlebell, moving the handle from the fingers to the palm, bringing it into contact with the wrist and forearm [11]. The kettlebell comes to rest in the overhead position whilst in fixation, and the process is then repeated (see Figure 1). It has been suggested that in the upwards and downwards phases the kettlebell follows somewhat different trajectories [1]. To our knowledge, only one study has examined the technique of the kettlebell snatch [12], reporting that novice participants extend the hips, knees and ankles simultaneously, and swing the kettlebell through the sagittal plane. The kettlebell snatch was further described to have rapid muscle activation-relaxation cycles, producing relatively large posterior shear forces on the spine [12].

This proposed trajectory of the snatch performed with a kettlebell appears quite different to that of the snatch performed with barbells or dumbbells. The barbell snatch and power snatch has been shown to follow an 'S' or reverse 'S' shaped trajectory, characterised by an initial small displacement of the barbell rearwards, then forwards and rearwards again [13, 14]. This type of trajectory allows the weightlifter to move through the first pull and transition phase, and to adopt the power position prior to the second pull. The power position may allow for the generation of very large power outputs during the second pull [15]. Elite weightlifters were found to have an anterior posterior range of -0.096±0.07 m during successful barbell snatch attempts. In contrast, the trajectory of a dumbbell power snatch is displaced forwards then rearwards [16].

During competition, the barbell snatch is performed with a bilateral grip for one maximal repetition. Conversely, the kettlebell snatch is performed unilaterally and traditionally utilises multiple repetitions in competitions. The duration and technique used in the upwards and downwards phases may both be of importance. Additionally, the kettlebells displaced centre of mass sits below the wrist. This makes it much harder to safely fail a single maximal lift of a kettlebell snatch, compared to that of a barbell or dumbbell snatch. This may suggest the kettlebell snatch is better suited to higher repetitions than the barbell snatch and as such may be a better tool for increasing energy expenditure and developing aerobic and anaerobic conditioning.

In comparison to the barbell snatch, the unilateral nature of the kettlebell snatch allows for greater degrees of freedom, which may result in a larger choice of techniques. However, the unique shape of the kettlebell may necessitate a modified approach to training and technique, in contrast to that of a barbell. The material and body of knowledge available to coaches regarding kettlebell exercises for training purposes is limited. The present study aimed to investigate the kettlebell trajectory of elite kettlebell lifters during the snatch. This information is especially important for coaches and strength and conditioning specialists looking to prescribe higher repetition snatch movements for their athletes. As a training tool, the kettlebell snatch may be better suited to higher repetitions. Comparatively, this may require different applications to that of the barbell snatch, traditionally utilising one repetition in competition.

METHOD

TESTING PROCEDURES

Four elite participants performed 16 repetitions over one minute with one 32 kg kettlebell. Repetitions 2-16 were compared to help determine the variation in the trajectory as these repetitions all had a downward phase preceding the upward. Kettlebell trajectory was captured with the VICON Motion Analysis System (250 Hz) and analysed with VICON Nexus (1.7.1). The cadence of 16 repetitions per minute was selected based on similar cadences sustained during either training or competition.

PARTICIPANTS

Four elite kettlebell sport athletes (originating in Russia or Kyrgyzstan), who had all won at least one world championship in biathlon (jerk and snatch) and/or held past or current world records in the snatch, were recruited. In their most recent competition, which occurred within 12 months of data collection, all lifters performed between 80-100% of the current world record number of lifts with a 32kg kettlebell for their respective weight categories. All participants held the rank of 'Master of Sport International Class' or 'Honored Master of Sport', (as issued by the Ministry of Sports of Russia, or the USSR State Committee for Physical Culture and Sport). The four participants had the following characteristics: age = 29-47 yr, body mass = 68.3-108.1 kg, and height = 1.72-1.89 m. This study was approved by the Institutional Review Board. Informed consent was given, in the presence of a translator if required.

PROCEDURES

Six VICON infrared cameras were placed around a weightlifting platform in a position to capture three dimensional motion of the kettlebell during the snatch. The infrared cameras captured the movement of reflective markers placed on the kettlebell. The system was calibrated dynamically by waving an L-wand with five reflective markers in the area that the kettlebell would pass through, in accordance to the manufacturer's instructions. This was repeated until all cameras had an RMS error under 0.2% [17]. The point of origin was then set in the middle of the platform, to calibrate the cameras positions. A professional-grade kettlebell (Iron Edge, Australia), with a mass of 32.1 kg was used as its dimensions are the standard requirement for kettlebell sport. Two markers (14 mm x 12.5 mm in diameter) were placed on the kettlebell at the base of each handle to avoid contact with the athlete and to ensure consistent position. Participants were required to perform a warm-up they would typically perform prior to performing the kettlebell snatch. Chalk, sand paper and a spray bottle were provided to ensure that the handle was prepared to their individual lifting requirements. After the marker set had been placed, each lifter stood on a platform and performed one set of snatches for 16 repetitions over 1 minute with their self-selected hand. This pace was selected as it was the competition pace for one or more of the athletes, was attainable by novice and intermediate athletes (albeit with lighter loads), and commonly performed in training and competition. An analogue clock was placed in view to allow consistent pace.

Kettlebell trajectory was subsequently determined by attaining the midpoint of the two markers. After each trial had been performed the markers were manually labelled using VICON Nexus software. A frame-by-frame review of each trial was undertaken to ensure there was minimal error caused by unlabelled markers. After this review took place a Woltering spline filter was applied to fill any gaps (less than 20 frames) in the trajectories [18]. These gaps in the trajectories were calculated by the markers past trajectory, velocity and acceleration.

Time displacement data was used to determine the trajectory and velocity in three dimensions of motion. For ease of interpretation resultant velocity was used. Four points of each repetition of the kettlebell trajectory were analysed: 1) fixation; 2) midpoint of the downwards phase; 3) end of the back swing; and 4) midpoint of the upwards phase (see Figure 2).

These four points were identified the moment the kettlebells trajectory changed from an anterior to posterior direction, or vice versa. The mean position from all 15 repetitions at these four points was the goal position. These four points were used as a reference to determine the error in one and two dimensions. The absolute error (AE, including vertical error, anterior-posterior error and medio-lateral error) illustrated the distance in metres from the goal in one dimension [19]. The radial error (RE, including sagittal plane error and frontal plane error) signified the distance in metres from the goal in two dimensions [19]. The RE was calculated by using the following formula:

Equation 1. (RE in the sagittal plane = $\sqrt{(Vertical\ error)^2 + (Anterior\ Poster)^2}$

Equation 2. (RE in the frontal plane = $\sqrt{(Vertical\ error)^2 + (Medio - Lateral\ error)^2}$

The anterior-posterior (AP), medio-lateral (ML) and vertical displacements were calculated from the end of the back swing to the midpoint of the trajectory for AP and ML, and to fixation for the vertical displacement range. Comparisons in the lifters' trajectories were also made using an anterior-posterior to vertical ratio (APV), and medio-lateral to vertical (MLV) ratio. The end of the back swing to fixation mean displacement range was used to determine the vertical portions of the ratios.

STATISITICAL ANALYSES

Data has been presented as means and standard deviations unless stated otherwise. Descriptive statistics were used to determine the amount of kettlebell AP, ML motion and variation for each lifter. Effect size (ES) and paired t-tests with two tails were used to compare the midpoint of the upwards and downwards phases for each repetition. The magnitude of the effect was considered trivial ES <0.2, small ES 0.2-0.6, moderate 0.6-1.2, large ES 1.2-2.0, very large ES 2.0-4.0 and extremely large ES > 4.0 [20]. The AE and RE for repetitions 2-16 were calculated. The first repetition was ignored because it started from the ground and not in fixation. The variation was determined at the same four points, listed above. AE was calculated in AP, ML and vertical planes of motion. RE was calculated in the sagittal and frontal planes.

RESULTS

TRAJECTORY

In the sagittal plane, the trajectory of the kettlebell snatch followed a C-path for all participants through the upwards and downwards phases (Figure 3). Figure 3 illustrates the kettlebell sagittal plane trajectory for the four subjects, whilst Figure 4 represents the kettlebell trajectory in the frontal plane of motion.

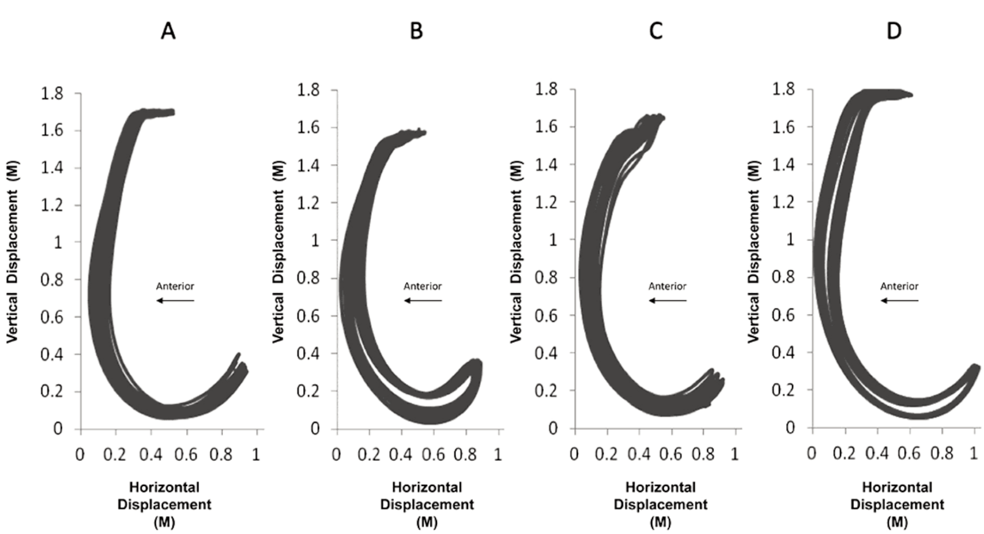

Figure 3. Sagittal plane kettlebell trajectory

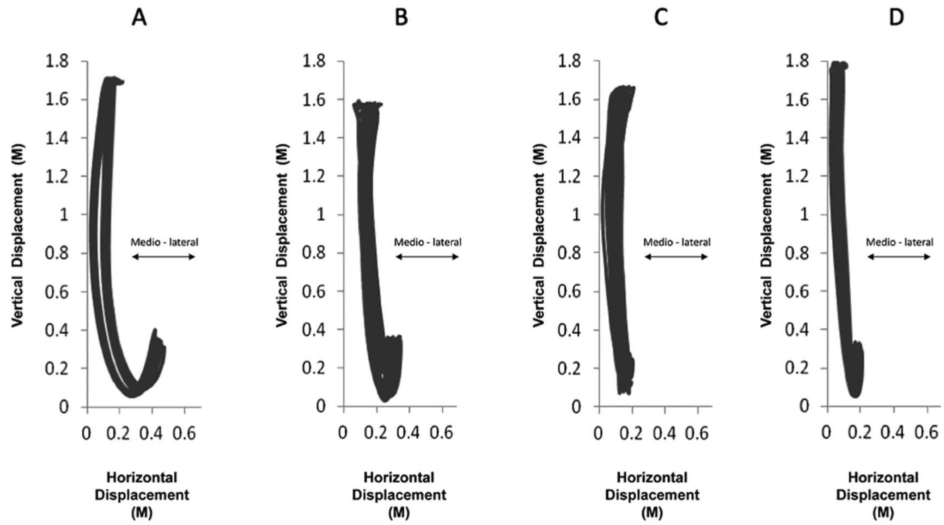

Figure 4. Frontal plane kettlebell trajectory

RATIOS AND DISPLACEMENT

Table 1 illustrates the kettlebell displacement ranges and ratios. The APV and MLV ratios indicate that the C-path followed a larger radius during the upwards than downwards phase for all participants. Participants B, C, and D had a relatively smaller MLV ratio ranging from 0.05-0.13 for both phases compared to participant A, who had a relatively larger MLV ratio of 0.31 ± 0.01 and 0.26 ± 0.02 for the upwards and downwards phases, respectively.

Table 1. Mean displacement ranges (m) and ratios for respective participants

	Lifter A	Lifter B	Lifter C	Lifter D				
	Up Phase	Down Phase	Up Phase	Down Phase	Up Phase	Down Phase	Up Phase	Down Phase
APV	0.67 ± 0.02	0.63 ± 0.03	0.66 ± 0.02	0.60 ± 0.02	0.60 ± 0.02	0.56 ± 0.02	0.66 ± 0.02	0.60 ± 0.01
MLR	0.31 ± 0.01	0.26 ± 0.02	0.13 ± 0.03	0.13 ± 0.03	0.05 ± 0.02	0.06 ± 0.02	0.08 ± 0.02	0.07 ± 0.01
Vertical	1.265 ± 0.024	1.265 ± 0.024	1.240 ± 0.020	1.240 ± 0.020	1.393 ± 0.016	1.393 ± 0.016	1.466 ± 0.020	1.466 ± 0.020
AP	0.845 ± 0.014	0.798 ± 0.027	0.820 ± 0.016	0.744 ± 0.025	0.834 ± 0.024	0.783 ± 0.035	0.967 ± 0.014	0.877 ± 0.016
ML	0.394 ± 0.018	0.329 ± 0.031	0.166 ± 0.036	0.165 ± 0.34	0.065 ± 0.026	0.080 ± 0.035	0.113 ± 0.015	0.103 ± 0.015

All data are mean + standard deviations. APV: Anterior-Posterior to Vertical ratio, MLV: Medio-lateral to Vertical ratio.

Table 2. Three dimensional ranges and effect size between the midpoint of the upwards and downwards phases (m)

	Lifter A	Lifter B	Lifter C	Lifter D
AP	0.049 ± 0.023**	0.076 ± 0.029**	0.046 ± 0.026**	0.090 ± 0.017**
ES	1.99	4.19	2.06	6.67
ML	0.070 ± 0.020**	0.018 ± 0.013	0.035 ± 0.022	0.014 ± 0.008*
ES	3.30	0.06	0.61	0.59
Vertical	0.022 ± 0.015**	0.062 ± 0.030**	0.034 ± 0.020	0.094 ± 0.028**
ES	1.29	3.45	0.51	5.34

All data are mean + standard deviations. AP: Anterior-posterior, ML: Medio-lateral,
*Significant difference in positions of upwards and downwards phases ($p < 0.05$),
** Significant difference in positions of upwards and downwards phases ($p < 0.01$).

Table 2 shows the AP, ML and vertical displacement ranges between the upwards and downwards phases. The downwards phase represents the smallest arc, compared to the upwards phase. The range between the upwards and downwards phases was largest in the AP, compared to the ML differences in all lifters.

VELOCITY

Participants' peak kettlebell resultant velocity ranged from moderate to extremely large ES difference, whereby the upwards phase was faster than the downwards phase for all lifters, except lifter A (see Table 3). Figure 5 shows the typical velocity of the kettlebell as it moved from the downwards phase to the upwards phase. The two peaks in velocity occurred approximately in the re-gripping phase and during the acceleration pull. The two noted times in which velocity reached zero were at fixation, and momentarily between the back and forwards swing.

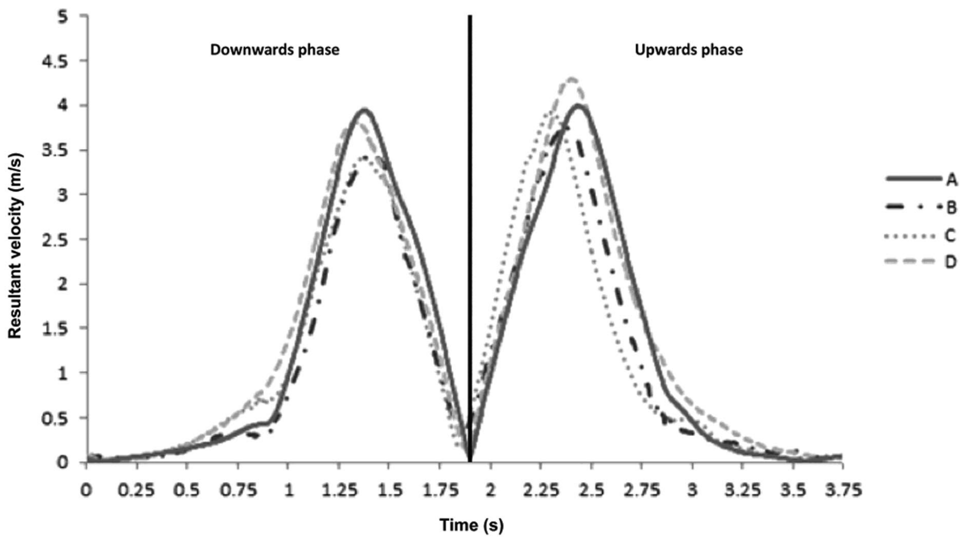

Figure 5. Typical kettlebell resultant velocity-time curve for respective participants

Table 3. Mean resultant velocity (m.s^{-1}) of respective participants

Phase	Lifter A	Lifter B	Lifter C	Lifter D
Upwards	3.95 ± 0.4	3.88 ± 0.03	4.03 ± 0.13	4.27 ± 0.04
Downwards	4.00 ± 0.04	3.52 ± 0.05	3.39 ± 0.09	3.83 ± 0.02
ES	-1.19**	7.45**	3.21**	12.05**

All data are mean
+ standard deviations.
** Significant difference in resultant velocity of upwards and downwards phases ($p < 0.01$).

MOVEMENT VARIABILITY

Table 3 shows AE, RE and displacement range for the three dimensions for each participant. The AE and the RE indicate that the kettlebell trajectory was highly consistent at each of the four points for all four participants.

Table 4. Displacement Range, Radial Error and Absolute Error for Respective Participants (m)

	Lifter A	Lifter B	Lifter C	Lifter D
Phase		**Anterior-Posterior**		
End Back Swing Range	0.054 ± 0.015	0.033 ± 0.012	0.072 ± 0.024	0.044 ± 0.012
AE	0.012 ± 0.09	0.010 ± 0.04	0.019 ± 0.013	0.010 ± 0.007
RE (APV)	0.023 ± 0.016	0.023 ± 0.09	0.024 ± 0.013	0.019 ± 0.012
Acceleration Pull Range	0.032 ± 0.009	0.058 ± 0.014	0.066 ± 0.023	0.050 ± 0.011
AE	0.008 ± 0.005	0.010 ± 0.010	0.019 ± 0.013	0.008 ± 0.008
RE (APV)	0.015 ± 0.008	0.017 ± 0.012	0.028 ± 0.014	0.015 ± 0.012
Fixation Range	0.039 ± 0.010	0.105 ± 0.028	0.094 ± 0.028	0.067 ± 0.021
AE	0.007 ± 0.006	0.022 ± 0.015	0.022 ± 0.017	0.018 ± 0.010
RE (APV)	0.008 ± 0.006	0.023 ± 0.016	0.023 ± 0.016	0.018 ± 0.010
Re-gripping Range	0.105± 0.026	0.069 ± 0.020	0.090 ± 0.023	0.050 ± 0.015
AE	0.016± 0.008	0.016 ± 0.011	0.017 ± 0.015	0.011 ± 0.008
RE (APV)	0.022 ± 0.020	0.024 ± 0.011	0.032 ± 0.027	0.021 ± 0.009
Phase		**Medio-Lateral**		
End Back Swing Range	0.062 ± 0.016	0.078 ± 0.024	0.051 ± 0.018	0.031 ± 0.009
AE	0.013 ± 0.010	0.019 ± 0.014	0.016 ± 0.007	0.007 ± 0.005
RE (MLV)	0.023 ± 0.016	0.023 ± 0.009	0.024 ± 0.013	0.019 ± 0.012
Acceleration Pull Range	0.051 ± 0.017	0.062 ± 0.016	0.056 ± 0.015	0.046 ± 0.012
AE	0.015 ± 0.008	0.015 ± 0.009	0.011± 0.009	0.008 ± 0.009
RE (MLV)	0.015 ± 0.008	0.017 ± 0.012	0.028 ± 0.014	0.015 ± 0.012
Fixation Range	0.062 ± 0.020	0.105 ± 0.026	0.090 ± 0.025	0.044 ± 0.014
AE	0.018± 0.009	0.019 ± 0.017	0.019 ± 0.016	0.012 ± 0.008
RE (MLV)	0.018 ± 0.008	0.020 ± 0.016	0.020 ± 0.015	0.012 ± 0.007
Re-gripping Range	0.097 ± 0.027	0.073± 0.018	0.108 ± 0.030	0.069 ± 0.019
AE	0.021 ± 0.015	0.014± 0.012	0.024 ± 0.013	0.015 ± 0.011
RE (MLV)	0.025 ± 0.017	0.023 ± 0.012	0.037 ± 0.027	0.023 ± 0.009
Phase		**Vertical**		
End Back Swing Range	0.093 ± 0.024	0.077 ± 0.022	0.058 ± 0.016	0.074 ± 0.020
AE	0.018 ± 0.015	0.019 ± 0.009	0.012 ± 0.009	0.015 ± 0.011
Acceleration Pull Range	0.044 ± 0.014	0.058 ± 0.016	0.069 ± 0.022	0.061 ± 0.016
AE	0.012 ± 0.007	0.011± 0.008	0.018 ± 0.011	0.012 ± 0.011
Fixation Range	0.004 ± 0.001	0.018 ± 0.005	0.019 ± 0.005	0.012 ± 0.004
AE	0.001 ± 0.001	0.004 ± 0.003	0.004 ± 0.003	0.003 ± 0.002
Re-gripping Range	0.055 ± 0.017	0.071± 0.019	0.144 ± 0.036	0.055 ± 0.018
AE	0.012 ± 0.008	0.015 ± 0.007	0.025± 0.024	0.015 ± 0.009

All data are mean + standard deviations. AE: absolute error, RE: radial error, APV: Anterior-Posterior to Vertical ratio, MLV: Medio-lateral to Vertical ratio.

DISCUSSION

Three dimensional motion analysis was used in this study to document kettlebell snatch kinematics performed by elite kettlebell athletes. The main findings were that despite some differences between the four athletes, significant commonalities emerged: 1) there was a 'C' shape trajectory during the downwards and upwards phases of the snatch; 2) the 'C' shape followed a narrower trajectory during the downwards phase; and 3) the resultant velocity time graph resembled an 'M' shape.

One marked similarity was the narrow 'C' shape trajectory on the way down and a wider 'C' shape on the way up. The smaller radius on the way down may be due to several reasons. During the initiation of the downwards phase it was noticed that all athletes moved their bodies away from the kettlebell. This allowed for the kettlebell to fall as closely as possible to the base of support. Following the initial counter movement the athlete flexes and supinates the elbow [1, 11]. The supination of the elbow may help to reduce the movement of the kettlebell through the AP plane and minimise grip stress (and subsequent fatigue) during the transition into the re-gripping phase. The flexion of the elbow may also minimise the AP movement of the kettlebell, thereby again placing the kettlebell as close to the base of support as possible. The large radius from the forwards swing to the start of the acceleration pull may help to minimise the centripetal force acting on the grip. Following the acceleration pull, the hand insertion phase guides the kettlebell onto the back of the wrist. The grip must relax during this phase to help facilitate a smooth transition into fixation. Reducing the stress on the grip may help to prolong performance as anecdotally grip endurance is considered the weakest link in elite GS athletes. Paying particular attention to the hand insertion will also help to reduce the potential for the kettlebell to have heavy contact upon the forearm, and therefore reduce the risk of musculoskeletal injury to the distal forearm. Strength and conditioning coaches need to be aware of this before their athletes progress the kettlebell snatch.

Movement was remarkably consistent for all athletes in the frontal and sagittal planes. This is most likely to minimise energy expenditure and therefore fatigue over the ten minute event. The most consistent of the four points was the fixation phase which had a RE range of 0.008 ± 0.006 m and 0.023 ± 0.016 m, in both sagittal and frontal planes. This would suggest that a consistent fixation phase is of the upmost importance. Low endpoint variability is most useful to ensure that the mass of the kettlebell is over the shoulder in all three planes. If this was not the case, greater energy and time would be used fixating or locking out the kettlebell overhead. Within the limitations of the research, it can be concluded that elite kettlebell sport athletes maintain a consistent trajectory, particularly at some of the key positions of the movement. Maintaining consistent fixation may be key in increasing the reproducibility of the trajectory as it marks the start and finish of the lift. The trajectory of the kettlebell for athletes A and C followed a similar path during both the downwards and upwards phases in the sagittal plane, while the vertical midpoints were at a relatively similar level for lifters A and C (0.022 ± 0.015 m and 0.034 ± 0.020 m trajectory difference, respectively). In contrast, the trajectory for athletes B and D were visibly separated and the vertical midpoint of the 'C' shape occurred in different vertical positions in the upwards and downwards phases (0.062 ± 0.030 m and 0.094 ± 0.028 m, respectively) (Figure 3). These differences in trajectory could be explained by: 1) greater trunk rotation in the acceleration pull phase; 2) the degree of plantar flexion in the upwards or downwards phase; 3) a larger shift backwards during the downwards phase; 4) the position of the upper extremity; and 5) possibly anthropometrical differences. Unfortunately, the present study only assessed the motion of the kettlebell, however, future studies may be useful to better describe the relationship between the kettlebell and lifters kinematics. Potentially, technique may differ over the course of the ten minutes due to fatigue or changes in cadence, however, these differences were beyond the scope of the present study.

Based on the kettlebell kinematics, it appears that different strategies were used to prolong performance in the different lifters. Lifter A displayed the largest MLV range in the upwards and downwards phases, which may produce fatigue in the contralateral musculature to a greater extent. In novice athletes, the mean activation of the lower erector spinae performing the kettlebell snatch with a sagittal plane trajectory was 54.2 ± 18.3 and 61.3 ± 16.3 % MVC for the ipsilateral and contralateral sides, respectively [12]. Lifter A may increase the demands of the contralateral musculature further by increasing the ML moment arm (which is reflected in his MLV ratio). This may increase the requirements of the torso to resist or control lateral flexion to a greater extent, in an effort to offset fatigue for the last five minutes. In doing so, they may possibly spare the ipsilateral side for subsequent effort following the hand switch as it will become the contralateral side at the five minute mark. Thus, having a larger MLV ratio trajectory may be a strategy to help spread the loading across different muscle groups during the left and right hand efforts. This strategy may be particularly useful during biathlon, as athletes must perform the jerk, which predominantly takes place in the sagittal plane one or two hours prior to the snatch, and may still be experiencing fatigue from this effort [3, 4]. Lifters B, C and D had much smaller MLV ratios compared to lifter A. The dominant AP trajectory in lifters B, C and D suggests that their strategy requires relatively symmetrical loading, resulting in less effort by a single muscle group, thus prolonging performance. A sagittal plane dominant trajectory similar to lifters B, C and D may offer strength and conditioning coaches a technique with the greatest ease of application. Conversely, lifter A's style may be useful in a GS setting; however, it would require a coach to monitor both sagittal and frontal planes of motion, with respect to the kettlebell trajectory.

As previously stated, upward phase horizontal displacement of the kettlebell was greater than the downward phase equivalent for all lifters, perhaps to reduce the centripetal load on the fingers. Increasing kettlebell velocity may further increase the centripetal stress on the fingers. Two peaks in velocity between the upwards and downwards phases were observed across all lifters. The first peak occurred approximately in the re-gripping phase, and the second generally in the acceleration pull phase. Lifters B, C and D had slower peak velocities in the downwards phase, whereas lifter A's peak velocity was greatest during the downwards phase. Reducing the velocity on the downwards phase could help to reduce stress placed on the finger flexors, but it could also increase the time needed to perform each repetition, which may be counter-productive to the objective of the sport which is to perform as many repetitions as possible in 10 minutes. Strength and conditioning coaches should be aware that in addition to the obvious effect of altering the kettlebell mass, different cadences and/or anthropometric factors may result in different kettlebell velocities. Therefore, an increase in cadence may result in greater velocity in the downwards phase and a faster eccentric phase. This increase in repetition velocity may result in greater grip and systemic fatigue, which may only be sustainable over shorter time periods.

PRACTICAL APPLICATION

The kettlebell snatch may be a useful option as an alternative to high repetitions of the barbell snatch, as it can be performed consistently. This may be particularly useful for strength and conditioning coaches, wishing to program an explosive total body movement such as the snatch for higher repetitions. Additionally, the unilateral and swinging nature of the kettlebell may provide a unique stimulus. Programming a snatch for higher repetitions may increase the metabolic and grip demands [5]. These components may also be important factors in sports that require a combination of strength and endurance qualities. Grip strength is an important component of Judo competition [21]. Grappling sports such as Judo, freestyle and Greco-Roman wrestling typically involve tournament formats and a progressive increase in fatigue and grip strength loss occurs with each bout during these tournaments [22-25]. The kettlebell snatch may have potential application in these sports, as it may promote increased levels of local muscular endurance. In contrast, the barbell snatch has been well researched and is an effective stimulus for power adaptations [15]. Its trajectory follows an 'S' shape which is predominantly vertical, allowing for positions which maximise power output. Therefore, the barbell snatch would be most appropriately programmed for lower repetitions, in contrast to the kettlebell snatch, which may be better suited to higher repetitions. The kettlebell snatch has a cyclical component, as it contains an upwards and downwards phase. Following a 'C' trajectory will help to prolong performance and in turn training volume, which may allow for greater training outcomes. Problems may arise if a lifter attempted to apply an 'S' trajectory to the kettlebell, which may not be appropriate or attainable, and may cause the hand insertion and fixation phases to occur too closely together (when the arm is vertical). This may lead to greater impact upon the forearm, thus increasing the risk of injury. Evidently, kettlebell snatch technique should not be taught in the same manner as the barbell snatch.

LIMITATIONS

The small sample size recruited is the major limitation within this research, but the athletes involved are all elite within GS, making them of particular interest. Due to time constraints and international travel stress, the lifters were unable to perform 10 minute sets at a competition pace for this study. This would have offered an insight into their trajectories in a fatigued state. A total of 16 repetitions were studied over one minute. The number of repetitions performed was at competition pace for the two lighter lifters. However, this was below competition pace for the two heavier lifters.

CONCLUSION

The kettlebell snatch trajectory of elite GS athletes follows a 'C' shaped path. There were two differently shaped 'C' trajectories, one with a smaller radius on the downwards phase, and the other a larger during the upwards phase. Kettlebell displacement occurred predominantly in the sagittal plane, although varying and relatively smaller amounts of horizontal displacement were recorded in the frontal plane. Within the upwards and downwards phases, low movement variability appears an important factor, particularly in the overhead fixation position. With the kettlebells potential large degrees of freedom, individual athlete style may affect their trajectories.

Additionally, there were two peaks in velocity which occurred in the upwards and downwards phases. This technique easily facilitates multiple repetitions due to its cyclical upwards and downwards phases. This research has shown that the kettlebell snatch can be performed with consistent kettlebell trajectories and velocities for 15 repetitions by elite GS athletes in a relatively unfatigued state.

ACKNOWLEDGMENTS

The authors would like to thank IKSFA (www.IKSFA.com), WKC (www.worldkettlebellclub.com), Sergey Rudnev and the other athletes for taking part in the research. No financial support was taken from these organizations. We would also like to thank Dr. Brett O'Connell for his technical support.

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Appendix iii: Study 2 Publication

External kinetics of the kettlebell snatch in amateur lifters

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ABSTRACT

Background: Kettlebell lifting has gained increased popularity as both a form of resistance training and as a sport, despite the paucity of literature validating its use as a training tool. Kettlebell sport requires participants to complete the kettlebell snatch continuously over prolonged periods of time. Kettlebell sport and weightlifting involve similar exercises, however, their traditional uses suggest they are better suited to training different fitness qualities. This study examined the three-dimensional ground reaction force (GRF) and force applied to the kettlebell over a 6 min kettlebell snatch set in 12 kettlebell-trained males.
Methods: During this set, VICON was used to record the kettlebell trajectory with nine infrared cameras while the GRF of each leg was recorded with a separate AMTI force plate. Over the course of the set, an average of 13.9 ± 3.3 repetitions per minute were performed with a 24 kg kettlebell. Significance was evaluated with a two-way ANOVA and paired *t*-tests, whilst Cohen's F (ESF) and Cohen's D (ESD) were used to determine the magnitude.
Results: The applied force at the point of maximum acceleration was 814 ± 75 N and 885 ± 86 N for the downwards and upwards phases, respectively. The absolute peak resultant bilateral GRF was 1,746 ± 217 N and 1,768 ± 242 N for the downwards and upwards phases, respectively. Bilateral GRF of the first and last 14 repetitions was found to be similar, however there was a significant difference in the peak applied force ($F\,(1.11) = 7.42$, $p = 0.02$, ESF = 0.45). Unilateral GRF was found have a significant difference for the absolute anterior–posterior ($F\,(1.11) = 885.15$, $p < 0.0001$, ESF = 7) and medio-lateral force vectors ($F\,(1.11) = 5.31$, $p = 0.042$, ESF = 0.67).
Discussion: Over the course of a single repetition there were significant differences in the GRF and applied force at multiple points of the kettlebells trajectory. The kettlebell snatch loads each leg differently throughout a repetition and performing the kettlebell snatch for 6 min will result in a reduction in peak applied force.

Subjects Bioengineering, Anatomy and Physiology, Kinesiology, Orthopedics
Keywords Resistance training, Strength endurance, Ground reaction force

Submitted 18 November 2016
Accepted 20 February 2017
Published 29 March 2017

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Academic editor
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Additional Information and Declarations can be found on page 12

DOI **10.7717/peerj.3111**

INTRODUCTION

Kettlebell sport, also referred to as girevoy sport (GS), competition originated in Eastern Europe in 1948 (*Tikhonov, Suhovey & Leonov, 2009*). In recent years, kettlebell lifting has gained increased popularity as both a form of resistance training and a sport. The kettlebell snatch is one of the most popular exercises performed with a kettlebell. The movement is an extension of the kettlebell swing, and involves swinging the kettlebell upwards from between the legs until it reaches the overhead position. To date, the barbell snatch has received much attention and reviews of the literature have demonstrated it to be an effective exercise for strength and power development (*Escamilla, Lander & Garhammer, 2000*; *Garhammer, 1993*). In contrast, the kettlebell snatch has only just started to receive research attention (*Falatic et al., 2015*; *Lake, Hetzler & Lauder, 2014*; *McGill & Marshall, 2012*; *Ross et al., 2015*).

In a classic kettlebell competition, the winner is the person who completes the most snatch lifts within a 10 min period. Current rules stipulate that the athlete can only change the hand holding the kettlebell once during this 10 min period. Additionally, to perform a valid repetition the kettlebell must be locked out motionless overhead at the conclusion of each repetition. The overhead position is known as fixation, which was found to have the lowest movement variability compared to the end of the back swing, and the midpoints of the upwards and downwards phases within its trajectory (*Ross et al., 2015*). It has been proposed that due to the kettlebell's unique shape and its resulting trajectory, the unilateral kettlebell snatch may be better suited for performing multiple repetitions than a single maximum effort (*Ross et al., 2015*). Specifically, the kettlebell snatch trajectory follows a 'C'-shaped path as it can move in between the athlete's legs (*Ross et al., 2015*), in contrast to an 'S'-shaped trajectory of the barbell snatch (*Ho et al., 2014*; *Newton, 2002*), which moves in front of the knees facilitating a double knee bend. In elite kettlebell sport, the kettlebell snatch also involves a downwards phase which follows a smaller radius compared to the kettlebell's upwards phase (*Ross et al., 2015*). The downwards phase gives the kettlebell snatch more of a cyclical natural than the barbell snatch, where the barbell is dropped from the overhead recovery position, thus providing a training stimulus in both the upwards and downwards phases.

The kettlebell snatch and barbell snatch move through a number of different phases that share some similarities. From the starting position, the barbell snatch has the following phases: first pull, transition, second pull and the catch phase (*Haff & Triplett, 2015*; *Ho et al., 2014*). In contrast, the kettlebell snatch starts at fixation and has the following phases: drop, re-gripping, back swing, forward swing, acceleration pull and hand insertion phase (*Ross et al., 2015*; *Rudnev, 2010*). The second pull has been shown to be the most powerful motion during the barbell snatch (*Garhammer, 1993*). Similarly, the acceleration pull phase has been suggested to be the most explosive phase of the kettlebell snatch (*Rudnev, 2010*).

There is currently little research on the kinetics of the kettlebell snatch. The only study to date recorded the bilateral ground reaction force (GRF) of the kettlebell swing

Figure 1 Illustrates the phases of the kettlebell snatch. (A) fixation, (B) drop, (C) re-gripping, (D) back swing, (E) forward swing, (F) acceleration pull, (G) hand insertion, (A) fixation.

and snatch (*Lake, Hetzler & Lauder, 2014*). The kettlebell snatch and two-handed swing were analysed over three sets of eight repetitions performed with the intention of achieving the maximum velocity possible, with horizontal and vertical work, impulse, mean force and power of the kettlebell snatch and swing calculated (*Lake, Hetzler & Lauder, 2014*). Both exercises had greater vertical impulse, work and mean force power than the horizontal equivalent regardless of phase (*Lake, Hetzler & Lauder, 2014*). The vertical component of the kettlebell snatch and two-handed swing were comparable, whilst the two-handed swing had a larger amount of work and rate of work performed in the horizontal plane (*Lake, Hetzler & Lauder, 2014*). One of the limitations was that GRF was investigated bilaterally when the movement is unilateral and is therefore likely to load the ipsilateral and contralateral legs differently (*Lauder & Lake, 2008*). This study investigated the hardstyle kettlebell snatch, which may have a different hip action, when contrasted with the kettlebell sport snatch. The hardstyle kettlebell snatch involves a single explosive leg extension. The upwards phase is described as being a swing, high pull and punch up (*Tsatsouline, 2006*). In contrast, the kettlebell sport snatch typically involves a double knee bend in an effort to improve the efficiency of the exercise. The double knee bend allows the kettlebell to transition forwards from the end of the back swing, before the explosive leg extension takes place (*Rudnev, 2010*). Although, there is inter-lifter variation within kettlebell sport technique (*Ross et al., 2015*), commonly kettlebell sport involves plantarflexion of the ipsilateral ankle during the explosive leg action (see Fig. 1), whilst this is not the case within the hardstyle snatch.

This study aims to build on the work by *Lake, Hetzler & Lauder (2014)* by investigating the unilateral GRF of the kettlebell snatch, throughout key positions of a single repetition and a prolonged set. In addition, force applied to the kettlebell by the lifter was also examined and will further the understanding of the kinetics of the key points of the trajectory outlined previously (*Ross et al., 2015*). These data will offer coaches an insight into the kinetic demands that the kettlebell snatch places upon the body providing insight to guide kettlebell exercise prescription.

METHODS

Study design

Twelve amateur kettlebell sport lifters performed 6 min of the kettlebell snatch exercise with one hand change, as is commonly performed in training by GS competitors. GRF was recorded with two AMTI force plates and kettlebell trajectory was simultaneously recorded with a nine-camera VICON motion analysis system. The GRF from the force plates allowed us to determine the external mechanical demands applied to the lifter and kettlebell system centre of mass, whilst the reverse kinematics calculated the force applied to the kettlebell. Force was determined using the kettlebell's known mass (kg) and the acceleration (m s^{-2}) determined via reverse kinematics. The aim was to identify the external demands placed upon each leg and the changes in kinetics during a prolonged kettlebell snatch set over 6 min. The dependent variables were resultant kettlebell force (N), resultant absolute and relative GRF (N) for: resultant, anterior–posterior, medio-lateral and vertical bilateral, GRF impulse (N s) and resultant velocity of the kettlebell (m s^{-1}). These were measured at the following time points: time of peak GRF, point of maximum kettlebell acceleration, point of maximum kettlebell velocity, end of back swing, lowest kettlebell point, midpoint and highest kettlebell point.

Subjects

Twelve males with a minimum of three years kettlebell training experience (age 34.9 ± 6.6 years, height 182 ± 8.0 cm and mass 87.7 ± 11.6 kg, handgrip strength non-dominant 54.5 ± 8.0 kg and dominant 59.6 ± 5.5 kg) gave informed consent to participate in this study. They were free from injury and their training regularly included 6 min kettlebell snatch sets. Prior to taking part in the study, the participants performed 6.0 ± 2.1 training sessions per week, of which 3.3 ± 1.9 were with kettlebells. All had previously competed in kettlebell sport and kettlebell sport was the primary sport for nine of the 12 participants. A 24 kg kettlebell was selected, as this is the weight used by 'amateur' lifters within a kettlebell sport competition. This is in contrast to 32 kg weight for 'professional' lifters and 16 kg for 'novice' lifters. The Australian Catholic University's ethics review panel granted approval for this study to take place (ethics number 2012 21V). All participants gave written consent to take part in this research.

Procedures

During a single testing session, athletes performed one 6 min kettlebell snatch set with a hand change taking place at the 3 min mark. A 6 min set was chosen as opposed to the GS standard 10 min set, as it was attainable for all subjects and is a common training set duration for non-elite kettlebell sport athletes. Handgrip strength was tested with a grip dynamometer with a standardised procedure 10 min pre-set and immediately post-test (*ACSM, 2013*). They were provided with chalk and sand paper (as this is standard competition practice) and asked to prepare the kettlebell as they would before training or competition. A range of professional-grade kettlebells of varying masses (Iron Edge, Australia) were available for the lifters to perform their typical warm ups. Following the athletes warm up, each 6 min set was performed with a professional-grade 24 kg kettlebell, as is the standard for kettlebell sport within Australia. Three markers were used, one (26.6 mm × 25 mm) was placed on the front plate of the kettlebell, and two markers (14 mm × 12.5 mm in diameter) were placed on the kettlebell at the base of each side of the handle. The markers were placed in these positions to help avoid contact with the lifter during the set. Nine VICON infrared cameras (six MX 13+ and three T20-S) sampling at 250 Hz, were placed around two adjacent OR6 AMTI force plates sampling at 1,000 Hz. The point of origin was set in the middle of the platform, to calibrate the cameras' positions. The athlete was instructed to stand still with one foot on each plate and the kettlebell approximately 20 cm in front of him before the start of the 6 min set in order to process a static model calibration. A self-paced set was then performed as if they were being judged in a competition. To initiate the set, the kettlebell was pulled back between the legs.

VICON Nexus software was used to manually label markers, and a frame-by-frame review of each trial was performed to minimise error. Average marker position was computed at rest from initial position. The initial position of the markers was used to compute vectors from centroid to the centre of gravity. Kettlebell motion was computed using singular value decomposition of the marker transformations into a translation, a rotation and an error value (*Duarte, 2014*). Root mean square error was calculated and time steps with high error values were dropped from analysis. The centre of gravity locations were computed from the translation and rotation of the kettlebell geometry. A third order B-spline was used to interpolate and filter the three-dimensional trajectories using the python function ('`scipy.interpolate.splprep`'). The spline functions ('`knots`') were then used to compute the velocity and acceleration.

Time steps of the kettlebells trajectory that contained the kettlebell maximum velocity, maximum acceleration (peak resultant kettlebell force) and the following points: end of the back swing, lowest point, midpoints and highest point (overhead lockout position) were identified. At these time steps the resultant kettlebell force, resultant bilateral GRF, and resultant velocity were recorded. Time steps moving from the overhead lockout position to the end of the back swing were allocated a relative negative time in seconds, with the end of the back swing as zero. The time steps from the end of the back swing moving to the overhead lockout were given a positive relative time. Over the entire set at the point that peak bilateral absolute resultant force or peak resultant force for the ipsilateral and contralateral leg was reached, the three-dimensional force was reported. In addition to the entire set, the three-dimensional bilateral forces were reported for the first and last 14 repetitions. Fourteen repetitions were chosen because it was the closest whole number to the mean repetitions per minute performed by the subjects over the 6 min. The forces were presented in both absolute units and relative to each subject's body mass. As the majority of the work occurred between the end of the back swing and the midpoint of the upwards and downwards phases of its trajectory, absolute and relative impulse for each leg was calculated over this period.

Statistical analyses

Data were placed into the Statistical Package for the Social Sciences (SPSS; IBM, New York, United States), Version 22. The data were screened for normality using frequency tables, box-plots, histograms, z-scores and Shapiro–Wilk tests prior to hypotheses testing. One univariate outlier was detected and removed from three of the data sets, relative unilateral vertical GRF, relative and absolute upwards phase medio-lateral GRF. In order to satisfy normality, the medio-lateral GRF for the absolute upwards phase was transformed using the base 10-logarithm function. Following data screening, the final sample numbered 11–12 participants.

A 2×2 two-way ANOVA was used to evaluate the difference within peak resultant kettlebell force, absolute and relative GRF for: resultant, anterior–posterior, medio-lateral and vertical bilateral vectors for both the first and last 14 repetitions and the upwards and downwards phases. Additionally, absolute and relative unilateral GRF vectors were compared with a 2×2 two-way ANOVA between the ipsilateral and contralateral legs as well as the upwards and downwards phases. Temporal measures of kinetics were compared within different points of the kettlebell trajectory with two-tailed paired *t*-tests and a Bonferroni adjustment. An intra-repetition analysis compared the kinetics at six points of the kettlebell trajectory (highest point, midpoints, lowest points and end of the back swing), additionally peak bilateral GRF, maximum acceleration and peak resultant velocity were compared to their peak value (this was done to determine the different demands throughout a single repetition). The magnitude of the effect or effect size was assessed by Cohen's D (ESD) for *t*-tests and Cohen's F (ESF) for two-way ANOVA. Trials from both right and left hands were assessed. If the lifter performed an uneven number of repetitions with each hand, the side with the greatest number had repetitions randomly removed in order to allow for an even amount of pairs. Removed repetitions were evenly allocated between each minute. Within each minute, randomly generated numbers corresponding to each were used to determine removed repetitions. The magnitude of the paired *t*-test effect was considered trivial ESD < 0.20, small ESD 0.20–0.59, moderate ESD 0.60–1.19, large ESD 1.20–1.99, very large ESD 2.0–3.99 and extremely large ESD ≥ 4.0 (*Hopkins, 2010*). Statistical significance for the paired *t*-tests required $p < 0.001$. The magnitude of difference for the two-way ANOVA was reported as trivial ESF < 0.10, small ESF 0.10–0.24, medium ESF 0.25–0.39 and large ESF ≥ 0.40 (*Hopkins, 2003*). The two-way ANOVA required $p < 0.05$ for statistical significance.

RESULTS

A total number of 972 repetitions were analysed for the 12 amateur kettlebell sport lifters, each performing an average of 13.9 ± 3.3 repetitions per minute. Grip strength of the hand that performed the last 3 min of the set had a reduction ($p = 0.001$, ESD = 0.77) of 9.8 ± 4.4 kg compared to pre-test results. Tables 1 and 2 show descriptive statistics for the three-dimensional GRF and kettlebell force during the first and last 14 repetitions for the absolute and relative values, respectively. The absolute peak resultant kettlebell force was significantly larger for the first repetition period compared to the last (i.e. first 14 vs last 14) when a full repetition was analysed (i.e. upwards and downwards phases combined) (F (1.11) = 7.42, $p = 0.02$, ESF = 0.45).

Tables 3 and 4 show the descriptive statistics for the absolute and relative GRF of the ipsilateral and contralateral leg. At the point of peak resultant GRF for either the

Table 1 Absolute mean (SD) resultant and three-dimensional GRF for the first and last 14 repetitions.

	First 14 repetitions		Last 14 repetitions	
	Downwards	Upwards	Downwards	Upwards
GRF (N)	1,766 (240)	1,775 (277)	1,782 (249)	1,797 (285)
GRF *x* (N)	47 (43)	70 (33)	59 (51)	63 (42)
GRF *y* (N)	308 (74)	299 (80)	320 (88)	315 (92)
GRF *z* (N)	1,736 (235)	1,746 (271)	1,748 (246)	1,766 (278)
Resultant peak kettlebell force (N)	809 (74)	895 (76)	826 (85)	879 (101)

Note:
x, medio-lateral, *y*, anterior–posterior, *z*, vertical.

Table 2 Mean (SD) resultant and three-dimensional relative GRF (normalised to body weight (N)) for the first and last 14 repetitions.

	First 14 repetitions		Last 14 repetitions	
	Downwards	Upwards	Downwards	Upwards
GRF (BW)	2.06 (0.24)	2.08 (0.31)	2.08 (0.24)	2.10 (0.31)
GRF *x* (BW)	0.06 (0.05)	0.08 (0.04)	0.07 (0.06)	0.07 (0.05)
GRF *y* (BW)	0.36 (0.08)	0.35 (0.10)	0.37 (0.10)	0.37 (0.11)
GRF *z* (BW)	2.03 (0.24)	2.04 (0.30)	2.04 (0.25)	2.07 (0.30)

Note:
BW, weight body; *x*, medio-lateral; *y*, anterior–posterior; *z*, vertical.

Table 3 Mean (SD) three-dimensional forces comparison of ipsilateral and contralateral with values shown as absolute values.

	Ipsilateral downwards	Contralateral downwards	Difference	Ipsilateral upwards	Contralateral upwards	Difference
GRF (N)	897 (133)	939 (175)	42 (4.6%)	936 (110)	949 (110)	13 (1.38%)
GRF *x* (N)	34 (16)	59 (56)	25 (53.7%)	46 (25)	33 (33)	13 (32.9%)
GRF *y* (N)	165 (42)	154 (38)	11 (6.9%)	164 (39)	146 (42)	18 (11.6%)
GRF *z* (N)	885 (126)	939 (166)	54 (5.9%)	905 (93)	942 (106)	37 (4.0%)
Resultant impulse (N·s)	380 (29)	365 (64)	15 (4.0%)	382 (52)	378 (63)	4 (1.0%)

Note:
x, medio-lateral; *y*, anterior–posterior; *z*, vertical.

ipsilateral and contralateral side, a large significant increase was found within the ipsilateral leg in the anterior–posterior vector ($F\,(1.11) = 885.15$, $p < 0.0001$, ESF = 7.00). In contrast, a large significant increase was found within the contralateral leg of the medio-lateral force vector over a full repetition for both the absolute GRF ($F\,(1.11) = 5.31$, $p = 0.042$, ESF = 0.67) and relative GRF ($F\,(1.10) = 9.31$, $p = 0.01$, ESF = 0.54). No significant differences were found for the absolute and relative impulse of the upwards or downwards phase. Figure 2 demonstrates a typical three-dimensional GRF of the ipsilateral and contralateral side.

Table 4 Mean (SD) three-dimensional forces comparison of relative GRF (normalised to body weight N) ipsilateral and contralateral legs.

	Ipsilateral downwards	Contralateral downwards	Difference	Ipsilateral upwards	Contralateral upwards	Difference
GRF (BW)	1.07 (0.14)	1.11 (0.15)	0.04 (3.7%)	1.13 (0.14)	1.11 (0.13)	0.02 (1.8%)
GRF *x* (BW)	0.04 (0.02)	0.08 (0.04)	0.04 (66.7%)	0.06 (0.04)	0.04 (0.04)	0.02 (40.0%)
GRF *y* (BW)	0.20 (0.05)	0.18 (0.04)	0.02 (10.5%)	0.20 (0.06)	0.16 (0.03)	0.04 (22.2%)
GRF *z* (BW)	1.04 (0.13)	1.07 (0.13)	0.03 (2.8%)	1.08 (0.19)	1.08 (0.12)	0 (0%)
Resultant impulse (BW·s)	0.42 (0.50)	0.44 (0.05)	0.02 (4.7%)	0.45 (0.05)	0.43 (0.05)	0.02 (4.6%)

Note:
BW, body weight; *x*, medio-lateral; *y*, anterior–posterior; *z*, vertical.

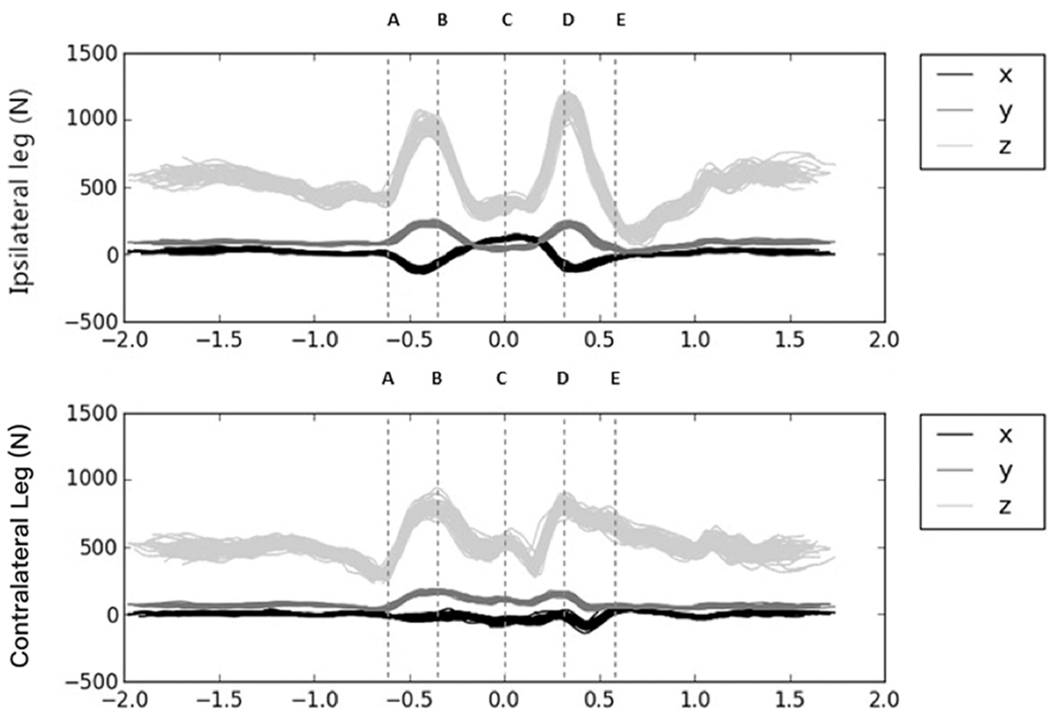

Figure 2 Typical three-dimensional GRF of the ipsilateral and contralateral legs for an 87 kg athlete. (A) midpoint (down), (B) lowest point (down), (C) end of back swing, (D) lowest point (up), (E) midpoint (up), *x*, medio-lateral; *y*, anterior–posterior; *z*, vertical.

Tables 5 and 6 provide data on how the kinematics and kinetics of the kettlebell snatch changed throughout the range of motion. Specifically, these tables list the relative times, resultant velocity and temporal changes in both kettlebell force and GRF with a comparison to their respective peak values during the downwards and upwards phases, respectively. Within the downwards phase there was no significant difference between peak bilateral GRF and bilateral GRF at the point of maximum acceleration, peak resultant velocity and resultant velocity at the midpoint. All other points had significant differences (see Tables 5 and 6).

Table 5 **Mean (SD) temporal measures of resultant kettlebell force, resultant velocity and resultant GRF of the downwards phase.**

	Relative time (s)	Resultant kettlebell force (N)	Resultant velocity (m/s)	Resultant bilateral GRF (N)
Highest point overhead	–1.72 (0.49)	222 (15)[1,5]	0.28 (0.22)[1,5]	1,054 (93)[1,4]
Midpoint	–0.60 (0.04)	284 (53)[1,5]	3.62 (0.21)[1,2]	866 (153)[1,5]
Peak resultant velocity	–0.53 (0.05)	466 (69)[1,5]	3.81 (0.21)	1,139 (165)[1,4]
Maximum acceleration	–0.40 (0.04)	814 (75)	3.23 (0.27)[1,4]	1,660 (299)
Peak resultant GRF	–0.34 (0.11)	775 (73)	3.08 (0.29)	1746.68 (217)
Lowest point	–0.31 (0.04)	694 (79)[1,3]	2.69 (0.34)[1,5]	1,595 (276)[1,2]
End of the back swing	0.00 (0.00)	127 (43)[1,5]	0.21 (0.08)[1,5]	940 (169)[1,5]

Notes:
The effect was trivial unless otherwise stated.
[1] Significantly ($p < 0.0001$) < peak value.
[2] Moderate ESD (0.6–1.2).
[3] Large ESD (1.2–2.00).
[4] Very large ESD (2.0–4.0).
[5] Extremely large ESD (>4.00).

Table 6 **Mean (SD) temporal measures of resultant kettlebell force, resultant velocity and resultant GRF during the upwards phase.**

n = 972	Relative time (s)	Resultant kettlebell force (N)	Resultant velocity (m/s)	Resultant bilateral GRF (N)
End of the back swing	0.00 (0.00)	127 (43)[1,6]	0.21 (0.08)[1,6]	940 (169)[1,6]
Lowest point	0.32 (0.05)	788 (112)[1,3]	2.90 (0.37)[1,6]	1,701 (320)[1,2]
Peak resultant GRF	0.33 (0.05)	798 (81)[1,3]	2.89 (0.52)[1,5]	1,768 (242)
Maximum acceleration	0.39 (0.04)	885 (86)	3.51 (0.29)[1,5]	1,634 (289)[1,2]
Peak resultant velocity	0.51 (0.05)	596 (62)[1,5]	4.16 (0.23)	1,095 (164)[1,5]
Midpoint	0.60 (0.04)	314 (38)[1,6]	3.82 (0.20)[1,4]	838 (122)[1,6]

Notes:
The effect was trivial unless otherwise stated.
[1] Significantly ($p < 0.0001$) < peak value.
[2] Small ESD (0.2–0.6).
[3] Moderate ESD (0.6–1.2).
[4] Large ESD (1.2–2.00).
[5] Very large ESD (2.0–4.0).
[6] Extremely large ESD (>4.00).

DISCUSSION

Three-dimensional motion analysis was used in this study to document kettlebell snatch kinetics of trained kettlebell sport athletes over a 6-min period. The main finding of this study was that the bilateral GRF was similar from the first and the last 14 repetitions, however, there were large significant differences within the resultant kettlebell force of the first and last 14 repetitions. Large differences were found between the ipsilateral and contralateral leg GRF within the anterior–posterior and medio-lateral vectors. Over the course of a single repetition, large differences in kettlebell force and GRF were evident as the kettlebell moved from the end of the back swing, to the lowest point, midpoint and highest point in the upwards and downwards phases. There were large differences in the bilateral GRF and the kettlebell force across different parts of the range of motion.

The kettlebell swing has received more attention than the kettlebell snatch in the scientific literature, possibly due to the relative ease of teaching and learning of the swing compared to the snatch. The kettlebell swing has been found to be an effective exercise for improving jump ability (*Jay et al., 2013*; *Lake & Lauder, 2012a*, *2012b*; *Otto et al., 2012*), strength (*Beltz et al., 2013*; *Lake & Lauder, 2012a*, *2012b*; *Manocchia et al., 2010*; *Otto et al., 2012*) and aerobic fitness (*Beltz et al., 2013*; *Falatic et al., 2015*; *Farrar, Mayhew & Koch, 2010*; *Hulsey et al., 2012*; *Thomas et al., 2013*). Additionally, the kettlebell swing was suggested to be a useful exercise for improving sprinter performance as it has a higher ratio of horizontal to vertical GRF compared to squat variations (*Beardsley & Contreras, 2014*). Previous research involving the (one armed) kettlebell snatch found the bilateral mechanical demands were similar to that reported for the two handed kettlebell swing in several ways (*Lake, Hetzler & Lauder, 2014*). For example, both exercises have a net vertical impulse greater than the net horizontal impulse (*Lake, Hetzler & Lauder, 2014*). Further, the marked difference between peak vertical and anterior–posterior GRF of the kettlebell snatch within this study support this. There appears to be little difference in the magnitude of the vertical impulse of the two kettlebell exercises, however, the horizontal impulse appears larger for the swing (*Lake, Hetzler & Lauder, 2014*). It is acknowledged that the two-handed kettlebell swing may be a more accessible choice for lower body power and strength training than the kettlebell snatch. However, the unilateral nature of the kettlebell snatch results in a different three-dimensional kinetic profile and may provide greater rotational core stability demands than the two-handed kettlebell swing. Muscle activation of the contralateral upper erector spinae has been shown to be higher than the ipsilateral portion of this muscle group during the one-armed swing and the same side during the two-armed swing (*Andersen et al., 2016*). Further, results of the current study indicated that the kettlebell snatch produced large effect size differences in two of the GRF vectors between the two legs. This suggests that the rotational component imposed different unilateral and force vector demands upon the entire body. The peak resultant force of the ipsilateral leg was found to occur later than the contralateral leg, which has also been shown in the unilateral dumbbell snatch (*Lauder & Lake, 2008*). This would suggest that during whole body exercises, holding the implement in one hand will place somewhat different demands, albeit of a modest magnitude, on the lower body even when it is functioning bilaterally.

This study demonstrates that with training, experienced kettlebell athletes are able to sustain consistent GRF over a prolonged 6-min set of kettlebell snatch, even though the kettlebell force over different points of the trajectory exhibited marked differences within each repetition. Interestingly, the peak resultant kettlebell force of the first 14 repetitions was significantly greater than the last 14 repetitions, suggesting that the kettlebell athletes were becoming fatigued at the end of the 6 min. This may be explained by the reduced handgrip strength that we observed, which anecdotally may be a limiting factor within kettlebell snatch competitions. The kettlebell athlete may attempt to take advantage of the less demanding phases of the kettlebell snatch to rest their grip, so as to prolong their performance.

Within different phases of the kettlebell snatch, there were marked differences in the intra-repetition kinetics. The differences in the kettlebell force throughout the range of motion may be an indicator of an efficient technique, thereby enabling prolonged performance of the kettlebell snatch. Peak resultant acceleration (in the upwards phase) occurred slightly after the lowest point of the trajectory, approximately after the kettlebell passed the knees. At the midpoint of the trajectory, the GRF of the upwards (838 ± 122 N) and the downwards phases (866 ± 153 N) was similar in magnitude to the body mass of the subjects (860 ± 113 N). The low GRF in the overhead position would suggest that the bulk of the lower body's workload takes place as the kettlebell moves from the midpoint to the end of the back swing and back to the midpoint of the kettlebell snatch. The midpoint of the snatch is similar to a swing end point, as the swing follows the same trajectory and is analogous to the barbell snatch pull within weightlifting. Interestingly, the end of the back swing for the kettlebell snatch has the lowest kettlebell force of 121 ± 45 N, which is approximately half the weight force (235 N) of the 24 kg kettlebells. It has been suggested that this is one of two points (along with the overhead fixation position) of relative relaxation in the kettlebell snatch (*McGill & Marshall, 2012*). In fixation, the arm is positioned overhead with the kettlebell resting on the back of the distal forearm, with the handle sitting diagonally across the palm. This position has been shown to exhibit low variability in elite kettlebell sport lifters (*Ross et al., 2015*). This low variability may promote metabolic efficiency and safety by reducing the muscular effort required to hold the kettlebell overhead, additionally it is necessary to perform a valid repetition within kettlebell sport. Comparatively, this may not be applicable to hardstyle kettlebell snatch technique, as this style has a focus on effectiveness, rather than efficiency and does not generally involve determining valid repetitions. Following the point of relaxation at the end of the back swing, the forward swing transitions the kettlebell past the knees where the acceleration pull occurs. The acceleration pull is the most explosive movement of the kettlebell snatch and serves a similar function to the second pull in weightlifting. Resultant maximum acceleration occurred slightly after the lowest point suggesting it starts as the kettlebell passes the knees during the forwards swing of the snatch. Peak barbell velocity marks the end of the second pull phase within the barbell snatch (*Ho et al., 2014*), which suggests that the point of peak resultant velocity marks the end of the acceleration pull phase. Peak resultant velocity occurs just before the midpoint of the upwards phase. The kettlebells backwards and forwards swing in the snatch is somewhat similar to the first pull and transition phase in the weightlifting pull. As the kettlebell swings forward, it is progressively accelerated, until peak acceleration when the body of the lifter is in a more advantageous position. By having peak acceleration as the kettlebell passes the knees, force may be applied more efficiently, much like the power position in the weightlifting pull (*Newton, 2002*). The changes in the force applied to the kettlebell during its trajectory have been found to occur in conjunction with sequential muscular contraction and relaxation cycles (*McGill & Marshall, 2012*). In addition to these rapid contraction–relaxation cycles, kettlebell sport athletes use the lockout or fixation position to briefly rest between repetitions. Controlling the kettlebell overhead allows a valid repetition, but it will also enable the athlete to regulate their pace, with longer and shorter pauses facilitating a slower or faster pace, respectively.

CONCLUSION

In summary, the GRF and force applied to the kettlebell changes during different stages of the kettlebell snatch. Additionally, the kettlebell snatch places different external demands upon the ipsilateral and contralateral legs within the AP and ML force vectors. Thus, despite the kettlebell snatch being performed with two legs, each leg may be loaded differently, thereby offering a different stimulus to each leg. There are rapid changes within the kinetics during different phases of the lift. In the upwards and downwards phases there were extremely large significant intra-repetition differences within GRF, kettlebell velocity and force applied to the kettlebell. Applied force to the kettlebell during the first and last 14 repetitions at the point of peak resultant kettlebell force is altered over the course of a prolonged set, possibly due to muscular fatigue, which is further supported by a marked reduction in hand grip strength. The data from this investigation suggest that the kettlebell snatch may provide a unique training stimulus, compared to other exercises (e.g. barbell snatch), as it has a downwards phase and places different demands upon the ipsilateral and contralateral legs. In addition, within their respective sports the barbell and kettlebell snatches sit on different ends of the strength–endurance continuum.

ACKNOWLEDGEMENTS

The authors would like to thank Angus McCowan for his assistance in the data analysis.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

The authors received no funding for this work.

Competing Interests

Justin W.L. Keogh is an Academic Editor for PeerJ.

Author Contributions

- James A. Ross conceived and designed the experiments, performed the experiments, analysed the data, contributed reagents/materials/analysis tools, wrote the paper, prepared figures and/or tables and reviewed drafts of the paper.
- Justin W.L. Keogh conceived and designed the experiments, wrote the paper and reviewed drafts of the paper.
- Cameron J. Wilson conceived and designed the experiments, wrote the paper and reviewed drafts of the paper.
- Christian Lorenzen conceived and designed the experiments, analysed the data, contributed reagents/materials/analysis tools, wrote the paper and reviewed drafts of the paper.

Human Ethics

The following information was supplied relating to ethical approvals (i.e. approving body and any reference numbers):

The Australian Catholic University's ethics review panel granted approval for this study to take place (ethics number 2012 21V).

Data Availability

The following information was supplied regarding data availability:

The raw data has been supplied as Supplemental Dataset Files.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.3111#supplemental-information.

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