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

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

**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 $4.03 \pm 0.20$ m s$^{-1}$, compared to $3.70 \pm 0.30$ m s$^{-1}$ during the downwards phase, and mean radial error across the sagittal and frontal planes was $0.022 \pm 0.006$ 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

# 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. 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 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 VO2peak 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 1 about here

Figure 2 about here

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 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 = $\sqrt{(Vertical\ error)^2 + (Anterior\ Posterior\ error)^2}$)

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.

**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 [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 about here

Figure 4 about here

## 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 about here

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.

Table 2 about here

## 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 about here

Table 3 about here

## 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 about here

# 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, 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). 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, 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.

## 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.

## 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, 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.

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**FIGURES**

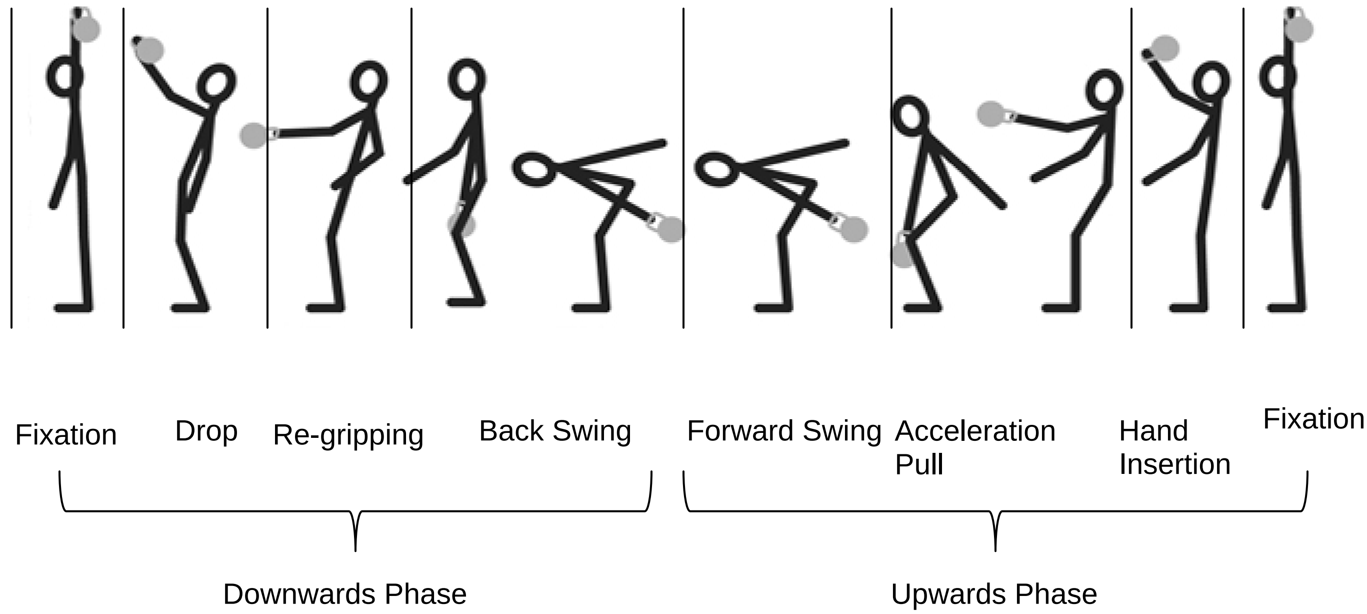


Figure 1. Phases of the kettlebell snatch.

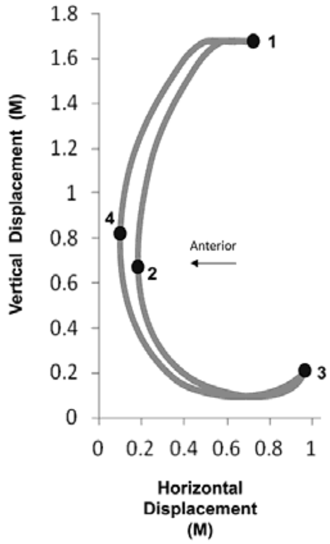


Figure 2. An example of the four points of error in the kettlebell snatch.

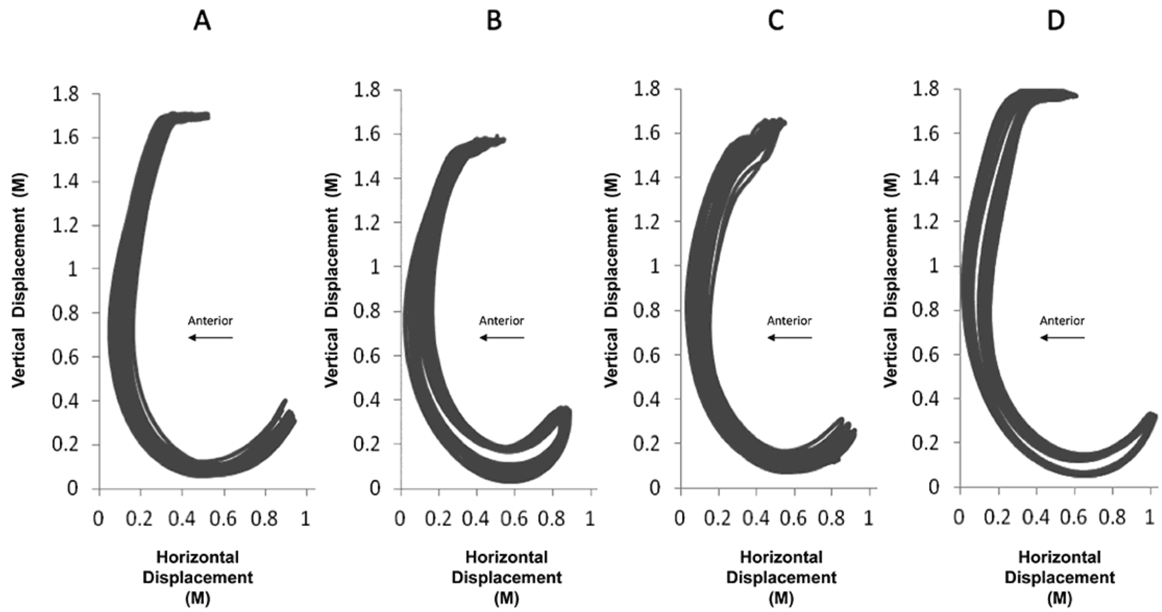


Figure 3. Sagittal plane kettlebell trajectory.

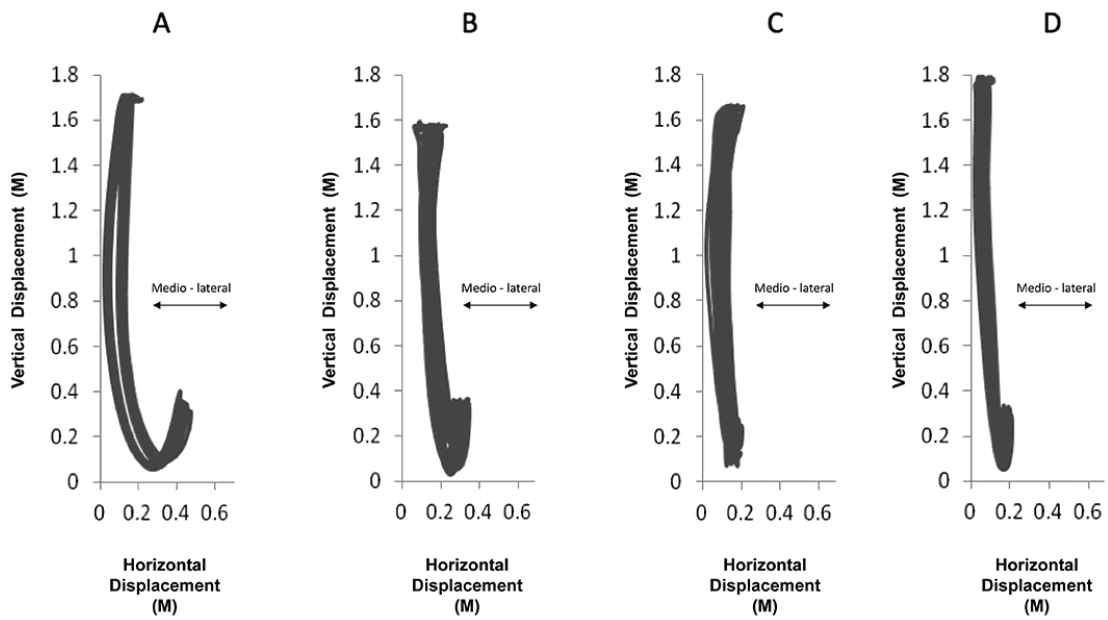


Figure 4. Frontal plane kettlebell trajectory.

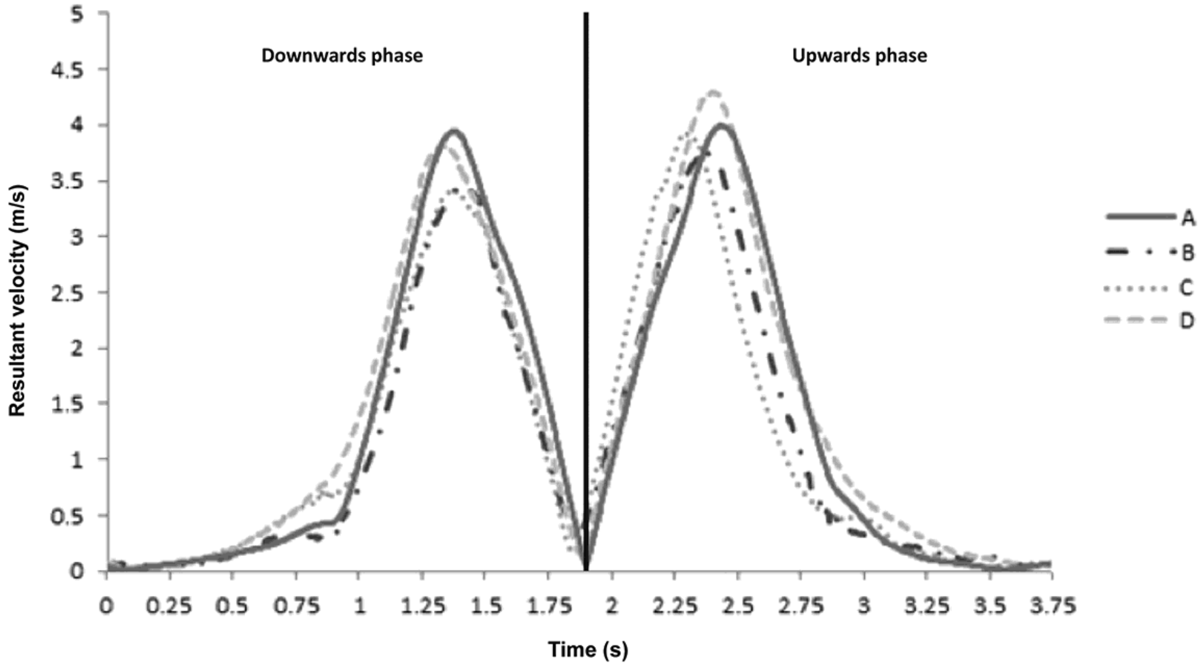


Figure 5. Typical KB resultant velocity-time curve for respective participants.

**TABLES**

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 Pha |
| 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 ± 0.0 |
| 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 ± 0.0 |
| 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 ± 0.0 |
| 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 ± 0.0 |
| 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 ± 0.0 |

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 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 ($p < 0.01$).

Table 3. 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 | 0.093 ± 0.024 | 0.077 ± 0.022 | 0.058 ± 0.016 | 0.074 ± 0.020 |

| | | | | |
|---|---|---|---|---|
| Range | 0.018 ± 0.015 | 0.019 ± 0.009 | 0.012 ± 0.009 | 0.015 ± 0.011 |
| AE | | | | |
| | | | | |
| 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±SD, unless otherwise stated. AE: absolute error. RE: radial error
APV: Anterior-Posterior to Vertical ratio, MLV: Medio-lateral to Vertical ratio.