Manuscript title: External kinetics of the kettlebell snatch in trained athletes

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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 et al. 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 score a point 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 trajectory 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 (Newton 2002), which moves around the knees. 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 it

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Comment [JL1]: It could be argued that the knees move to avoid the barbell forming part of the 'double knee bend' 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 though 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 catch phase (Haff & Triplett 2015). 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 phases (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 and snatch (Lake et al. 2014). The kettlebell snatch and two handed swing were analysed over three sets of eight maximum effort repetitions, 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).

Comment [JL2]: Clarify please – there seems to be a word missing

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Comment [JL3]: ‘though’ or ‘through’?

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Comment [JL4]: or maybe ‘...repetitions performed at the maximum velocity possible...’?

Comment [JL5]: Excellent – I wish I’d done this!

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.

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Comment [JL6]: I think it could be useful to provide a brief explanation about the subtle and in some cases not so subtle differences between the sport and hardstyle kettlebell snatch, particularly the emphasis that is typically put on the different hip actions

METHODS

Study Design

Twelve trained kettlebell lifters performed six minutes of the kettlebell snatch exercise with one hand change, as is commonly performed in training by GS competitors. Ground reaction force (GRF) was recorded with two AMTI force plates, and kettlebell trajectory was simultaneously recorded with a nine camera VICON Motion Analysis System. Force was determined using the kettlebell's known mass (kg) and the acceleration ($m.s^{-2}$) determined via reverse kinematics. The aim was to identity the external demands placed on each leg and the changes in kinetics during a prolonged kettlebell snatch set over six minutes. The dependent variables were: GRF (N), applied force (N), 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 backswing, lowest kettlebell point, midpoint and highest kettlebell point.

Comment [JL7]: Were they competitive GS athletes or recreational trainers who'd played around with some form of kettlebell snatch?

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Comment [JL8]: Is this 'kettlebell force'? If so, maybe you could have centre of mass force (from GRF) and kettlebell force (from kinematics)?

Subjects

Twelve males with a minimum of three years kettlebell training experience (age 34.9 ± 6.6 yr, height 182 ± 8.0 cm 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. 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.

Comment [JL9]: As with the above point, was Hardstyle or GS technique emphasised? There are big differences that will almost certainly influence your outcome

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 ten 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 24kg 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 (250 Hz) were placed around two adjacent AMTI force plates (1000 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 six minute set in

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Comment [JL10]: Please provide equipment details 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 (SVD) 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 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 force applied to the kettlebell, resultant GRF, and resultant velocity were recorded. Time steps moving from the overhead lockout position to the end of the backswing were allocated a relative negative time in seconds, with the end of the backswing as zero. The time steps from the end of the backswing 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

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Comment [JL11]: Why did you choose and use this approach?

Comment [JL12]: Is this 'resultant' as in the vector sum of the three orthogonal axes? If so, was this the case for 'kettlebell force' too? Please clarify 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, impulse for each leg was calculated over this period.

Comment [JL13]: Was kettlebell and lifter weight subtracted first?

Statistical Analyses

Data were placed 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 applied force, absolute and relative resultant, anterior-posterior, medio-lateral and vertical bilateral GRF 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 time steps of the kettlebell trajectory with two-tailed paired t-tests and a Bonferroni adjustment. Within

Comment [JL14]: Please revise once clarified above. I think the above could and needs to be clearer

Comment [JL15]: All time steps? Please clarify a repetition, the resultant velocity, bilateral GRF and applied force of different time steps were compared to their peak value.

Comment [JL16]: Why? Please explain why you did this? Were you trying to identify progressive repetition decline in these variables?

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 $\geq$ 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 $\geq$0.40 (Hopkins 2003). The two-way ANOVA required $p < 0.05$ for statistical significance.

RESULTS

A total number of 972 repetitions were analyzed for the twelve 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 1 and 2 show descriptive statistics for the three dimensional GRF and applied force during the first and last 14 repetitions for the absolute and relative values, respectively. The absolute peak applied 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 1. about here

Table 2. about here

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 unilateral GRF over an entire repetition, 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 impulse of the upwards or downwards phase. Figure 1 demonstrates a typical three dimensional GRF of the ipsilateral and contralateral side.

Figure 1. about here

Table 3. about here

Table 4. about here

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,

Comment [JL17]: Which side? Please clarify

Comment [JL18]: So where you describe 'resultant' force above you're actually referring to 'force'? Please clarify resultant velocity and temporal changes in both applied 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 & 6).

Table 5 about here

Table 6 about here

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 applied force of the first and last 14 repetitions. Large effect size 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 backswing, to the lowest point, midpoint and highest point in the upwards and downwards phases. There were large differences in the bilateral GRF and the applied force across different parts of the range of motion.

Comment [JL19]: Please clarify re above

Comment [JL20]: I'd suggest including this if it is indeed the case

Comment [JL21]: Picky, but aim for consistency throughout with this sort of thing please

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Comment [JL22]: Kettlebell force?

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Comment [JL23]: ???

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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; Lake & Lauder 2012b; Otto III et al. 2012), strength (Beltz et al. 2013; Lake & Lauder 2012a; Lake & Lauder 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). 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). 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 then 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. 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's functioning bilaterally.

Comment [JL24]: Yes – this is key!

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This study demonstrates that with training, experienced kettlebell athletes are able to sustain consistent GRF and applied force to the kettlebell over a prolonged six-minute set of the kettlebell snatch, even though the applied force over different points of the trajectory exhibited marked differences within each repetition. Interestingly, the peak applied 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. This supports the anecdotal evidence that grip strength is 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 applied force throughout the range of motion may be indicative of an efficient technique, thereby enabling prolonged performance of the kettlebell snatch. Peak 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 force 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 endpoint, 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 applied force of 121 ± 45 N, which is approximately half the weight force (235 N) of the 24

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Comment [JL25]: Vertical acceleration?

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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 wrist, with the handle sitting diagonally across the palm. This position has been shown to exhibit low variability in elite kettlebell lifters (Ross et al. 2015). This low variability may promote metabolic efficiency and safety and is necessary to score a point within kettlebell sport. Following the point of relaxation at the end of the backswing, 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. Maximum acceleration occurred slightly after the lowest point suggesting it takes place as the kettlebell passes the knees during the forwards swing of the snatch. The kettlebell's 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 will not only score a point, but it will enable the athlete to regulate their pace, with longer and shorter pauses facilitating a slower or faster pace, respectively.

Comment [JL27]: It may be worth pointing out here that this isn't necessarily the case with the Hardstyle snatch?

Comment [JL28]: Again, is this vertical or resultant acceleration? Also, peak acceleration doesn't mark the end of the acceleration phase so maybe consider peak velocity as has often been done in the weightlifting research

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CONCLUSION

In summary, the GRF and force applied to the kettlebell changes during different stages of the kettlebell snatch. In addition, 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. During the upwards phase and downwards phases there were extremely large significant differences within GRF, kettlebell velocity and force applied to the kettlebell. Applied force on the kettlebell of the first and last 14 repetitions at the point of maximum acceleration 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).

Comment [JL29]: Do you mean there were phase-to-phase differences in these dependent variables? This could be clearer

Comment [JL30]: How do some of your key data compare to data from some of the key snatch biomechanics papers?

ACKNOWLEDGMENTS

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

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Figures

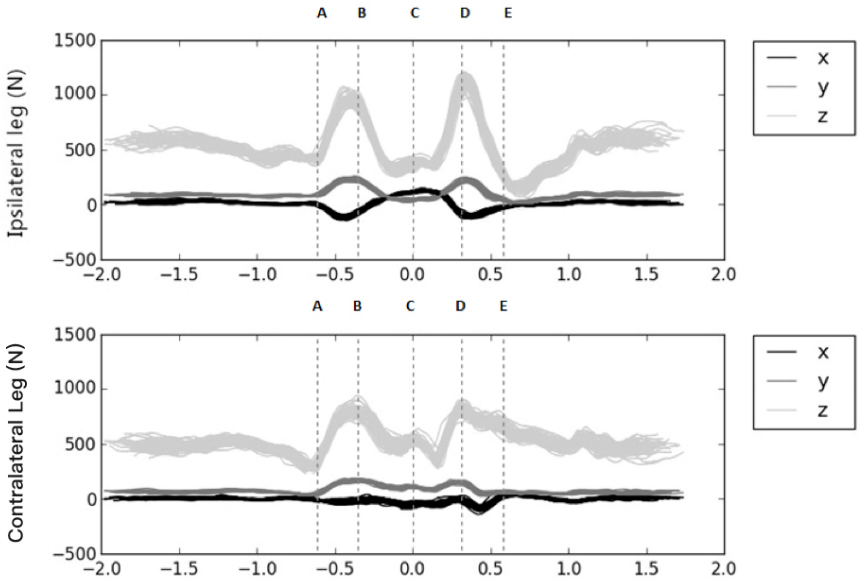

Figure 1. Typical three dimensional GRF of the ipsilateral and contralateral legs for an 87 kg athlete. A = Midpoint (down), B = Lowest point (down), C = End of backswing, D = Lowest point (up), E = Midpoint (up), x= medio-lateral, y = anterior-posterior, z = vertical.

Comment [JL31]: This is awesome!

Tables

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)	1766 (240)	1775 (277)	1782 (249)	1797 (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)	1736 (235)	1746 (271)	1748 (246)	1766 (278)
Maximum acceleration (N)	809 (74)	895 (76)	826 (85)	879 (101)

x= medio-lateral, y = anterior-posterior, z = vertical.

Comment [JL32]: I'm not sure I understand what you've done here? Please clarify

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 (N)	2.06 (0.24)	2.08 (0.31)	2.08 (0.24)	2.10 (0.31)
GRF x (N)	0.06 (0.05)	0.08 (0.04)	0.07 (0.06)	0.07 (0.05)
GRF y (N)	0.36 (0.08)	0.35 (0.10)	0.37 (0.10)	0.37 (0.11)
GRF z (N)	2.03 (0.24)	2.04 (0.30)	2.04 (0.25)	2.07 (0.30)

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		Contralateral	
	Downwards	Upwards	Downwards	Upwards
GRF (N)	897	936	939	949
	(133)	(110)	(175)	(110)
GRF x (N)	34	46	59	33
	(16)	(25)	(56)	(33)
GRF y (N)	165	164	154	146
	(42)	(39)	(38)	(42)
GRF z (N)	885	905	939	942
	(126)	(93)	(166)	(106)
Impulse N·s	380 ± 29	382 ± 52	365 ± 64	378 ± 63

x= medio-lateral, y = anterior-posterior, z = vertical.

Comment [JL33]: Is this 'resultant' impulse or impulse applied in a particular direction? Please clarify

Comment [JL34]: A minor consistency point, but I think the SD should be in parentheses to match the rest of the table.

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

	Ipsilateral		Contralateral	
	Downwards	Upwards	Downwards	Upwards
GRF (N)	1.07 (0.14)	1.13 (0.14)	1.11 (0.15)	1.11 (0.13)
GRF x (N)	0.04 (0.02)	0.06 (0.04)	0.08 (0.04)	0.04 (0.04)
GRF y (N)	0.20 (0.05)	0.20 (0.06)	0.18 (0.04)	0.16 (0.03)
GRF z (N)	1.04 (0.13)	1.08 (0.19)	1.07 (0.13)	1.08 (0.12)
Impulse N·s	0.42 (0.50)	0.45 (0.05)	0.44 (0.05)	0.43 (0.05)

x= medio-lateral, y = anterior-posterior, z = vertical.

Comment [JL35]: Please see above point on impulse

TABLE 5. Mean (SD) temporal measures of applied force, resultant velocity and resultant GRF of the downwards phase.

	Relative time (s)	Applied Force (N)	Resultant velocity (m/s)	Resultant Bilateral GRF (N)
Highest point overhead	- 1.72 (0.49)	222 (15)$^{\dagger+}$	0.28 (0.22)$^{\dagger+}$	1054 (93)†*
Midpoint	-0.60 (0.04)	284 (53)$^{\dagger+}$	3.62 (0.21)†‡	866 (153)$^{\dagger +}$

Comment [JL36]: Please clarify, is this resultant force and is it the force applied to the kettlebell?

Peak resultant velocity	-0.53 (0.05)	466 (69)$^{\dagger +}$	3.81 (0.21)	1139 (165)$^{\dagger *}$
Maximum acceleration	-0.40 (0.04)	814 (75)	3.23 (0.27)$^{\dagger *}$	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)$^{\dagger \#}$	2.69 (0.34)$^{\dagger +}$	1595 (276)$^{\dagger \ddagger}$
End of the back swing	0.00 (0.00)	127 (43)$^{\dagger +}$	0.21 (0.08)$^{\dagger +}$	940 (169)$^{\dagger +}$

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)

TABLE 6. Mean (SD) temporal measures of applied force, resultant velocity and resultant GRF during the upwards phase.

(n=972)	Relative time (s)	Applied 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)[†‡]	2.89 (0.52)[†*]	1768 (242)
Maximum acceleration	0.39 (0.04)	885 (86)	3.51 (0.29)[†*]	1634 (289)[†§]
Peak resultant velocity	0.51 (0.05)	596 (62)[†*]	4.16 (0.23)	1095 (164)[†*]
Midpoint	0.60 (0.04)	314 (38)[†+]	3.82 (0.20)[†#]	838 (122)[†+]

The effect was trivial unless otherwise stated.
[†]Significantly ($p<0.0001$) < Peak
[§]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)