Weightlifting: An Applied Method of Technical Analysis

Authors:

Shyam Chavda [1,2] – MSc CSCS ASCC CES, Mark Hill [2], Stuart Martin [2] - BSc, Anna Swisher [3] – PhD, CSCS, G Gregory Haff [4,5] – PhD, Anthony N Turner[1] – PhD ASCC CSCS*D

Institution:

1. London Sports Institute, Middlesex University, London, UK.
2. British Weightlifting, Powerbase Gym, Loughborough, UK.
3. USA Weightlifting, 1 Olympic Plaza, Colorado Springs, CO.
4. Centre for Exercise and Sport Science Research, Edith Cowan University, Joondalup, Australia.
5. Directorate of Sport, Exercise and Physiotherapy, University of Salford, Salford, Greater Manchester, UK

Correspondence:

Email: s.chavda@mdx.ac.uk

Tel no.: (+44)20 8411 2854

Address: as per above

Shyam Chavda is the programme lead for the MSc in Strength and Conditioning distance education at the London Sport Institute, Middlesex University. He is also the performance scientist for British Weightlifting and head coach at Middlesex University weightlifting club.

Stuart Martin is the Talent Pathway Manager at British Weightlifting.

Mark Hill is the Workforce Manager at British Weightlifting and is also the head coach at Locker 27 weightlifting club, Surrey.

Anna Swisher is Coach Development and Sport Science Manager at USA Weightlifting, Colorado Springs.

G. Gregory Haff is a Professor of Strength and Conditioning and course coordinator of the MSc in Exercise Science (Strength and Conditioning) at Edith Cowan University. He is also an Honorary Professor in the Directorate of Sport, Exercise and Physiotherapy at the University of Salford.

Anthony N Turner is an associate professor in Strength and Conditioning, and director of postgraduate programmes at the London Sport Institute, Middlesex University.

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Abstract

Weightlifting is a highly technical sport which is governed by interactions of phases to optimise the load lifted. Given the technicality of the snatch and clean and jerk, understanding key stable components to identify errors and better prescribe relevant exercises are warranted. The aim of this article is to present an applied method of analysis for coaches that considers the biomechanical underpinnings of optimal technique through stable interactions of the kinetics and kinematics of the lifter and barbell at key phases of the lift. This paper will also look to discuss variable components which may differentiate between athletes and therefore provide a foundation in what to identify when coaching weightlifting to optimise load lifted whilst allowing for individual variances.

Introduction

Weightlifting is a sport consisting of 2 lifts: the snatch and the clean and jerk (C&J). Weightlifting technique is rooted in placing the body in positions of strength and stability, where leverage is optimized and the body is capable of producing high levels of force thus allowing it to apply mechanical work to the barbell (21). As coaches, it is important to understand that a lifter's ability to effectively move the barbell from the floor to over-head (snatch or jerk) or to the shoulders (clean) is dependent on specific, key positions being met. Energy transference from skeletal muscle through the skeletal lever system will aid in the ideal organisation of movement and therefore the trajectory of the barbell (22). Given the high technical requirements of weightlifting, its foundations should be based on, and further quantified by, biomechanical principles, which allows for further insight in to how to maximise performance (46). Within the sport of weightlifting, success is determined by the load lifted, achieved via the generation of force, which is optimised by maintaining specific positions, at specific phases, which stay within the optimal biomechanics of the individual. Deviations are likely to cause a negative effect within the lift and lessen the chance of success. Therefore, within each phases of the snatch and clean and jerk, specific components must be met as a minimum, in order to successfully execute the lift (Table 1).

A technical model provides a framework, that can be adapted to an individual athlete biomechanical profile and should not serve as a constraint. Therefore, individual technical variances should be considered when coaching weightlifting, based on nationality (i.e. comparing one country to another) and the coaching philosophy adopted by that nation (39, 55). Furthermore, the style an individual adopts based on these variances and their anthropometrics should also be considered when coaching. Adjusting for individual variances and style should not impair optimal lift biomechanics, but instead help optimise them based on an individual's lever lengths, strength and mobility or limiting factors that cannot be changed (e.g. surgical impediment, joint restrictions, etc). On observation of the literature it becomes apparent that three commonalities exist between the snatch and the clean; key positions, barbell kinetics and kinematics, and temporal force-time characteristics, with the subtle differences of magnitude of force and barbell position relative to the body during the power position and the catch. It is important that coaches understand why specific components of the lift must be met in order to optimise the ability to lift the given load and to better identify whether a technical error is occurring. A greater appreciation for applied biomechanics in weightlifting enables coaches to better identify what key limiting factors to look for and provides a foundation to develop easy to understand, effective coaching points for the lifter. Furthermore, it provides a method of standardising the way coaches can monitor technique with minimal equipment, thus taking a more objective approach to identifying change.

Therefore, the aim of this article is to present an applied method of analysis for weightlifting that considers the biomechanical underpinnings of optimal technique through the stable interactions of the kinetics and kinematics of the lifter and barbell at each key position of the lift. This paper will also look to discuss variable components which allow for individual variances and how these should remain within the stable components discussed. Since similarities exist between the key positions for the snatch and the clean, the authors will discuss each phase related to both lifts simultaneously.

INSERT TABLE 1 AROUND HERE

The Set (Starting) Position

Stable Components

In determining the effectiveness of the first pull, the set position (Table 2) can often be overlooked. It has previously been postulated that the start position during a snatch underpins the success of the lift (37) When the lifter addresses the barbell, it should be placed directly above the point at which the CoP is being applied, which should be in the mid foot (23) (Figure 2). This should correspond to the approximately the first lace of the shoe. Any variation to this may mean the lifter is likely to shift their CoP unfavourably later on in the lift, thus increasing horizontal displacement of the barbell away from them and decreasing the chance of success (55). Once the barbell is positioned close to the lifter's base of support (BoS), the lifter should adopt a hook grip which has previously been shown to positively affect the kinetics, kinematics, and load lifted of a clean when compared to using a closed grip (53) and should therefore be introduced early to novice weightlifters. The grip adopted by the lifter will be determined by the lift they are performing and their arm length and will help provide a greater level of consistency when making contact in the 2nd pull. Figure 3 depicts the different ways grip can be objectively determined for the snatch and clean (10, 61).

Once the barbell has been gripped, the “slack” that exists between the barbell and the knurling should be taken out whilst simultaneously bracing the abdominals and extending the spine into neutral. Taking slack out, allows the lifter to smoothly displace the barbell (i.e. squeezing the barbell from the floor) as appose to “ripping” the barbell off the floor. “Ripping” the barbell off the floor is likely to cause small perturbations, and therefore compromise the structural integrity of the setup, potentially causing negative consequences further into the movement. Additionally, ensuring the slack is taken out of the barbell may help to reduce the electromechanical delay, therefore reducing the time between muscle stimulation and mechanical force output. The initial rise in vertical ground reaction force (vGRF) is instigated by slack being taken out of the barbell (Figure 4) and the lifter using the barbell to get into the set position (41).

The shoulder position relative to the barbell will be influenced by the height of the hips, however, it is commonly accepted that the shoulders should be over the barbell in the set position (17). This has shown to range from 3.6 ± 1.3cm to 6.9 ± 4.3cm for the snatch and the clean, respectively, in elite lifters (41). From a practical point of view, identifying the lifter’s armpit crease being directly above the barbell indicates that the joint centre of the shoulder is in front of the barbell and the lifter is therefore in the optimal position. Using this landmark on the body alleviates the question of “what part of the shoulder should be over the barbell?” and helps standardise communications and analysis across coaches. Once in position, the arms should be straight, and the elbows externally rotated to help facilitate a more favourable barbell trajectory during the second pull.

Variable Components

It has previously been suggested that the height of the hip-crease should be greater than the top of the knees (17), however, arm-, lower limb- and torso- length will influence this, as would dorsiflexion of the ankle. In order to satisfy the stable component of having the shoulders in advancement of the barbell, a lifter with a longer lower limb to torso length ratio would favour from starting the hip crease higher than the top of the knee, whereas those with a ratio favouring a longer torso and shorter lower limbs, may benefit from starting with the hip crease either in-line or slightly lower, than the top of the knee. In both instances, the arm pit crease remains above the barbell (Table 2). It should also be noted that passive dorsiflexion occurring at the ankle would need to be greater the lower a lifter sits. This will in turn mean the knee angle is more acute and over the barbell (5), therefore requiring more knee extensions, and possibly a straighter barbell path when attempting to clear the knees during the first pull. Foot width of an individual will also vary depending on the genetic predisposition of the femoral head within the acetabulum. The authors suggest the foot position should adopt a base similar to that of a vertical jump, given that the athlete will be triple extending during the second pull, and therefore needs to produce high magnitudes of force. The rotation of the foot, although variable, should be considered to help explain its effect on the athlete's BoS. Figure 1 outlines 3 different styles which a lifter may adopt.

INSERT FIGURE 1 AROUND HERE

INSERT FIGURE 2 AROUND HERE

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The First Pull

Stable Components

The importance of the first pull is unparalleled and has found to discriminate elite and district level weightlifters, where elite lifters displayed greater relative maximal force than district level lifters (41). The first pull has typically been referred to as a strength orientated movement (25), as the athlete must produce enough GRF to overcome the barbell's inertia (37), therefore making it significantly longer than all other phases (45). The technique of the first pull has previously been outlined (16, 17, 19). Its initiation has been defined as the moment of separation between the weight plate and the floor (19), and is also the point at which the lift has officially started (1). Empirical research has typically defined the end of the first pull as when the knees reach first maximal extension (2, 3, 9, 28, 35, 39, 50), however, other research has also determined it as; the most rearward position of the barbell before reaching peak velocity (52), and when the barbell has cleared the knees (38). The former is typically used within research looking at joint kinematics and is likely more useful when in a practical setting, as it is easier to define even when limited to using only live observational analysis and video capture.

During the initial displacement of the barbell, CoP on the foot moves towards (not on) the heel (23) (Figure 4), and the knees start to extend with the moment arm around the hip staying relatively unchanged (6). This allows a path for the barbell to move back towards the knee and is evidenced across a range of weightlifting populations (2, 4, 12, 27-29, 63). The extension of the knees and the relative consistency of the hip angle also provides a stretch reflex response in the hip and knee complex (41), which in turn has been posited to enhance the concentric portion of the pull (22).

In summary, the stable components to identify an appropriate first pull would be for the knees to reach peak extension, which is likely to elicit a shin angle near vertical. With the relatively constant moment around the hips, the torso angle should remain the same, thus leaving the crease of the armpit in advance of the barbell, further facilitated by the barbell moving back toward the knee. Observational analysis should also look for the system (barbell and lifter) to move in unison, as to allow for optimal force transference into the barbell.

Variable Components

The action of the first pull can often be achieved in numerous ways. For example, some lifters may use a countermovement prior to the barbell being displaced and others may set themselves and pull from stationary. These styles have previously been termed "dynamic" and "stationary" starts (19). Regardless of the style an individual uses, it is important that the barbell is not displaced too quickly as it may cause a decrease in vertical velocity of the barbell during the transition (5). Due to anthropometric differences between lifters, the knee and torso angle achieved during the end of the first pull will inevitably differ, but in most cases, would not violate the stable components previously mentioned.

The Transition

Stable Component

The transition is a phase often defined as when the knees first start to flex following the end of the first pull and moving into the power position (first maximum knee flexion) (9, 26, 35). The execution of the transition has been shown to occur in a short space of time, executed between 0.10 – 0.15 s (2, 9, 26, 45), facilitated by the stretch reflex elicited during the first pull (56). Previous research has often illustrated vertical barbell velocity to plateau or continually rise in more experienced weightlifters (9, 40), with some lifters showing a slight decrease (5, 18, 24). Displaying a decrease in barbell velocity during this phase may have negative connotations on the system, as the lifter will now have to overcome the decrease in barbell velocity, by having to re-apply more force into the floor and barbell to achieve a velocity which allows for optimal barbell displacement to facilitate the catch (26, 40). Research from Gourgoulis et al. (28) had shown that adult male national weightlifters who displayed a decrease in barbell velocity during the transition, also displayed a greater percentage of their maximum velocity (81.8%) (achieved at the end of the second pull), whereas those that did not have a decrease in velocity only reached 70.5% of their peak velocity which was associated to either the first pull being too fast, or fatigue. This was previously raised by Bartonietz (5) who suggested that movement coordination should result in a continual increase in barbell velocity and that a dip in velocity maybe associated with too fast a first pull, or weak hip extensors, and that training should address these issue. However, it has been postulated that a slight decrease in energy (and therefore velocity) of the barbell during the transition is acceptable due to improved mechanical advantages and re-employment of the knee extensor over their optimum range for force production (18).

To optimise the transition period, a lifter's CoP will shift from near the heel to the mid foot (23), with the lifter ideally staying flat footed throughout. During the transition, the lifter reduces the vGRF applied to the system to help aid the repositioning of the knee joint under the barbell, as well as aiding the ankles to passively dorsiflex and the torso to become more upright; these result in the power position, just prior to where peak vGRF is achieved. From transition to power position, the barbell should have travelled to its furthest point toward the lifter, meaning it is kept over the BoS, which can be observed by checking if the end of the barbell is directly above the mid-part of the foot.. The foot should be flat so the BoS is greater thus facilitating a larger vGRF and for the plantarflexion of the ankles to contribute to the triple extension during the second pull. The key here is to ensure the barbell is kept close to the body to optimise vertical force being applied into the bar during the second pull.

Variable Components

The degree of knee flexion and the rate at which this occurs during the transition will vary between individuals based on their lower limb lengths and the availability of passive ankle dorsiflexion. For example, as the knees feed through the bar the angle of the knee and hip during this transition, in addition to the anatomical stature of the lifter, will dictate where the bar is situated when in the power position. During the transition a lack of passive dorsiflexion would likely raise the athlete onto the forefront of the foot which as they feed the knee through, is undesirable as mentioned in the stable components, but this may also be a product of altered movement strategy to accommodate the load and is often observed in world class lifters when lifting maximal loads. Alternatively, this observation can also be prevalent with lifters that are using loads too high for their current level of development and therefore require the appropriate technical training and strength development at this phase. While the authors have discussed this to be a stable component which should be reinforced during training and the early stages of learning of weightlifting, it is worth noting that an early heel rise during the transition maybe become prevalent at maximal loads.

The Power Position and The Second Pull

Stable Components

The second pull has been a focal point of investigations within the sport of weightlifting (6, 8, 20, 25-29, 34-36, 38, 45, 55) and has been investigated alongside its derivatives as a method of improving force generating capabilities in non-weightlifting athletes (13, 14, 43, 49, 57-60). The definition of the second pull has previously been defined in a number of ways with the primary focus on the change in knee joint angle. For example, early literature from Häkkinen (33) and Kauhanen, Häkkinen and Komi (41) define the second pull as the transition or knee bend phase, with first peak knee flexion to maximal knee extension termed as the “third pull”. Although the terminology, “third pull” is now uncommon in the weightlifting community, a majority of literature has gone on to define the second pull as the point of first maximum knee flexion to the second maximal knee extension (2, 5, 6, 11, 26-29, 35, 39). Using the knee joint angle as a means to identify the start and end of the phase far outweighs other methods which have been used and require additional technologies (47, 54); this also provides clear start and end points to help standardise analysis. The start of the second pull is often termed the power position and defines the end of the transition. The optimal position of the knee and hip is difficult to gauge as a stable component, without the use of motion capture. Previous research from Haff et al. (31, 32) has derived the power position from national level weightlifters, and measured their force generating capabilities utilising the isometric mid-thigh pull (IMTP). This surrogate measure of weightlifting performance has been further investigated with the optimal hip and knee angle shown to be between 140-150° and 125-145°, respectively, depending upon the athlete's individual anthropometric profile (7, 15). This is difficult to observe when a lifter performs a clean or snatch, therefore a more viable option would be to identify the centre of the shoulder joint is slightly behind the bar with a vertical torso, and the bar directly over the mid foot, where the CoP is distributed, with the feet flat. (Figure 2). This should allow for individual variances while optimising force generation when executing the second pull, which is critical when lifting maximal loads. During the end of the second pull, the extension of the hip, knee, and ankle (plantarflexion), contribute to the high barbell velocity relative to all other positions, thus allowing for the barbell to be displaced at an optimal height for the catch. Research from Kipp (44) on the clean pull, found that the relative importance of the hip, knee, and ankle net joint moments, were 23, 31 and 46% for barbell velocity, and 23, 39 and 38% for barbell acceleration respectively. Specific to the second pull, plantarflexion and peak net joint moments in the ankle have been shown to be an important factor in weightlifting execution and as load increases (5, 42). Due to the aggressive plantarflexion of the ankle, the CoP will be on the ball of the foot, with the heel raised and the ankle, knee, and hip extending. The body relative to vertical line from the ankle (lateral malleolus) will have the shoulders being behind it, to help counterbalance the load in front. This has previously been presented by Kauhanen, Häkkinen and Komi (41), who found shoulder position to be -10.1 ± 1.3cm and -7.3 ± 2.6cm behind the barbell during the snatch and clean respectively, in elite Finnish weightlifters. Following this phase, the barbell reaches its peak velocity (34) and is also the point at which the barbell will start to displace horizontally due to the thigh or hip contact. Therefore, coaches should identify the stable components as the weight being distributed onto the forefront of the foot with the ankle, knee, and hips extended. This may display a shin angle near to the vertical plane and therefore give an indication as to whether the athlete is optimising vertical force, and not directing it in a direction which would cause them to jump too far back. The barbell relative to the body should remain close to the BoS, with horizontal displacement being minimised.

Variable Components

As explained during the transition phase the synchronisation of knee flexion, passive dorsiflexion and hip extension in addition to torso, arm, and lower body length will alter the placement of the barbell during the power position (start of the second pull), between individuals. Therefore, using generalised terms such as the "mid-thigh" for the clean or "hip" for the snatch may not always be appropriate to describe the power position. If, for example, during a snatch, a lifter displays the aforementioned stable components with the shoulder joint centre between the ankle and mid-foot and the front of the knee between the forefront of the foot and beyond, but they have long arms which grips the bar collar to collar, it is likely the bar will not sit in the inguinal hip crease. For the lifter to do this the torso angle would have to increase, meaning the shoulder joint will move outside of the BoS and likely reduce the vGRF applied to the ground. This may also consequently make the lifter jump backwards or disassociate their CoM from the bars CoM increasing the distance between the two.

Therefore, when teaching the power position, the coach may want to have the lifter set up in a way which satisfies the stable components in mind and allow the lifter to familiarise themselves with a position that is appropriate for them. This should also be reflected in using non generalised coaching cues such as “bar in hip pocket” (for the snatch) and should provide coaches with a means to individualise the coaching cue used to emphasise the position of the bar relative to the individual’s anthropometry and thus position.

The degree of extension at the ankle, knee, and hip will be dependent on the load and the velocity the barbell is travelling. Heavier loads near to or exceeding 1RM, would mean the athlete would require greater torque at the ankle, knee, and hip, and greater vGRF to propel the barbell to an optimal height. However, given that a higher magnitude of force must be produced during this phase in a relatively confined amount of time, the athlete may begin the turnover under the barbell at terminal extension, thus not achieving full extension. The degree of horizontal barbell displacement away from the lifter will be dependent on how effectively the athlete can transfer vertical force into the barbell and limit forward horizontal acceleration (20).

The Turnover

The turnover can be defined from the second maximum knee extension to the moment at which peak barbell height is achieved, and the lifter has begun to descend underneath it in preparation to receive the bar (Table 3) (2, 9, 11, 26-29, 35, 39). Given that peak barbell height can only be accurately determined using vertical displacement or velocity (i.e. velocity at peak height = $0\ m \cdot s^{-1}$), it would be difficult to present stable components for those without accessibility to the relevant technology; however, a brief overview highlighting occurrences during the turnover is provided. It has been shown that weightlifters achieve a barbell height of 60-70% and 55-65% of their height for the snatch and clean, respectively (8, 26, 47). Previous literature has reported elite weightlifters display lower relative percentages compared to lower performing weightlifters (6, 8, 41), but conflicting evidence exists where Chiu and colleagues found significantly greater relative heights in higher performing elite Taiwanese weightlifters (12), with Liu et al (47) finding similar results in elite Chinese lifters compared to sub-elite. Although conflicting evidence exists it should be noted that as load increases, as is the intention in weightlifting, vertical displacement will decrease, therefore the findings from Chiu and colleagues (12) and Liu et al (47) should be interpreted with caution and may indicate that those particular athletes were not near maximal load for the respective lift.

Following peak barbell height, the distance the barbell drops to the catch position has previously been considered an important factor for effective technique (40). It has been postulated that a larger drop distance infers that the lifter has displaced the barbell vertically higher than necessary in preparation for the catch (26). However, Chiu, Wang and Cheng (12) suggested that achieving a higher peak height allows the athlete to gradually slow the barbell's drop velocity and that better performing lifters are able to utilise this cushioning technique, thus displaying greater drop heights.

Another factor to consider during the turnover is the displacement and speed of the lifters centre of gravity (CoG). It has been shown that higher skilled lifters have a faster movement under the barbell as displayed by an increase in their CoG velocity (8). This is also highlighted when comparing successful and unsuccessful snatches and maximal versus sub-maximal loads, where successful and maximal loads show an increase in velocity of CoG between the end of the second pull and peak bar height (30, 48). Given the speed of the descent, it becomes difficult to identify stable components which are able to be seen through live observational analysis, however, it can be postulated that flexion of the knees should have begun in preparation for the catch when the barbell is at its peak height and the athlete should be descending into the receive position. Although three typical barbell trajectories exists (62) (pg88), a common trajectory throughout international and European weightlifters (4), suggest that the peak is achieved slightly behind the initial set position of the barbell. This is further supported by Stone (55) who found that the peak bar height is not achieved as far back in successful versus unsuccessful lifts (12.5 cm vs 16.6cm). However, it should be noted that variances in trajectory type and height achieved exist within the literature and therefore coaches should identify a common successful trajectory for lifters individually, should they have the necessary tools available.

The Receive and Catch

The receive and the catch can be defined as two distinct points within the lifts. Receiving the barbell during the snatch and clean can be defined as the moment the barbell achieves its lowest vertical velocity and is equal to 0 acceleration (Figure 4). This positive acceleration being applied to the bar suggests that resistance has been applied and the lifter is likely now in control of the bar. The catch however, can be better defined as the moment the athlete has stabilised the barbell at its lowest displacement (Table 3), with barbell acceleration and velocity stabilising around 0 $m \cdot s^{-2}$ and 0 $m \cdot s^{-1}$, respectively (Figure 4). Previous literature has defined the catch in various ways, with the general definition being that the bar is going from its maximal height to stabilisation, in a maximum squat position for both the snatch (2, 9, 11, 26, 28, 35, 39, 50) and clean (3). This leaves much to debate as the terminology “catch” has been used within the definition and the term stabilisation should be quantifiable when relating to the barbell. Therefore, Nagao (52) went on to better identify the catch as being the time when the vertical component of the barbell velocity was closest to 0 $m \cdot s^{-1}$ following maximum barbell height.

Stable Components

The issue with defining the receive and the catch using barbell acceleration and velocity is its inaccessibility to coaches. Therefore, for those that do not have access to such tools, they may define the receive as; the moment in which the athlete begins to visibly resist the barbell during its descent, which coincides with the moment prior to when the barbell begins to deform. The catch can therefore be identified as the point the lifter is visibly motionless at the bottom of their squat position prior to the recovery. During these two points, the barbell should be directly over the middle of the foot to ensure the load stays close to the athlete's centre of gravity, and over the BoS.

Variable

As previously mentioned, during the turnover phase the barbell may start to move behind the vertical intercept from the barbell centre in the set. The position the barbell is caught relative to this intercept has previously varied between weight classes (4) and has also been a discriminatory factor in successful versus unsuccessful lifts (2, 55). Providing the bar is caught over the lifter's BoS, then its position relative to the intercept may not be such an issue providing it is within their natural variance of technique. It may, however, highlight potential deficits in the application of vertical force into the barbell which may need addressing in prior phases of the lift.

The Recovery

The recovery from the snatch and clean should display similar qualities with the exception of where the bar is being held. In both instances, the weight distribution on the feet should remain on the mid foot, with the bar remaining directly over its BoS, and the legs straight. Ideally from the catch, the bar should move directly upwards with little horizontal deviation. During the recovery for the snatch, the arms must be locked, feet must be parallel, and the athlete must remain motionless in order for it to be valid under competition regulation (1). Since the lifter must execute a jerk following the clean, the recovery of the clean requires the athlete to potentially reposition the arms and feet that allow them to effectively jerk the barbell. This may be displayed by the athlete recovering from the clean and driving up to the forefront of the foot near maximal knee extension, in order to propel the bar upwards to reposition their hands for the jerk. Whether the lifter adopts this approach would not change the fact that the bar remains resting on the clavicle close to the neck, as to keep the barbell directly over the BoS with the lifter having to finish motionless with the feet parallel (1).

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Conclusion and Practical Applications

As is the case with complex motor skills, weightlifting requires considerable practice over time to attain a high level of skill mastery (51). It becomes clear that trying to standardise and objectify the analytical process of weightlifting becomes difficult without the use of video capture and/ or velocity and acceleration-time curves. It is likely that many coaches have access to cameras on their smart devices which capture at a rate in excess of what has been used in the seminal research. Therefore, capturing videos and images using the provided information to identify whether stable components have been met will allow the coach to better determine where the limiting technical factor of the lift exists and therefore enable them to best prescribe the appropriate exercises. Furthermore, this will help standardise "in gym" analysis and terminology, therefore allowing coaches and athletes to better identify if meaningful changes in technique have occurred.

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Definitions	
Stable Component	Variable Component
Specific elements within the lift which relate to joint, centre of pressure and barbell position relative to the body to help optimise the amount of weight lifted. Any compromise from the stable component will hinder the lift and likely cause an error or miss.	This may relate to the anthropometry of the athlete and their style of lifting and will therefore vary on an individual basis. The stable component should not be compromised and the variation in someone's position and/or trajectory should still meet the stable criteria.
Base of Support (BoS)	
Area of the feet which is in contact with the surface of the ground.	
Centre of Pressure (CoP)	
The distribution of force to an area of contact (feet) on the surface. (Robertson, pg 94,2014)	

Table 1. Definition of the proposed components of the weightlifting technical model.

Set	End of 1st Pull	Power Position	End of 2nd Pull
1st Pull		*Transition*	*2nd Pull*
			
Stable Components			
• Weight distribution mid foot. • Barbell over arch of foot. • Arm pit crease directly above the barbell.	• Weight distribution toward the heel. • Barbell moves toward lifter. • Barbell over ankle joint. • Shin angle near vertical. • Armpit crease in advance of the bar. • Relative back angle from set consistent.	• Weight distribution on mid foot. • Barbell moves toward. • Barbell directly in contact with lifter and over BoS. • Centre of shoulder between vertical intercept of ankle or forefront of foot.	• Weight distribution of forefront of foot. • Shin angle near vertical.
Variable Components			
• Height of hip relative to knee. • Foot position (i.e. width and angle)	• Knee angle. • Initiation of 1st pull (i.e. Dynamic or static)	• Position of barbell relative to the thigh (clean). • Hip and knee angle.	• Horizontal displacement of barbell relative to athletes BoS.
Positional Video Capture			
• 1 frame prior to plate separation from floor.	• Frame at which the knee joint reaches maximal extension.[a] • Frame prior to the shin angle moving away from the lifter.[b]	• Frame at which the knee is at 1st peak flexion.	• Frame at which peak knee extension occurs.

a = 45 degree capture; b = sagittal plane capture.

Table 2. Components of the pull

Turnover	Receive	Catch	Recovery
Peak Bar Height			
			
Stable Components			
• Lifter has begun the descent. • Knees flexed.	• Bar over arch of foot.	• Weight distribution on mid foot (i.e. no visible raising of heel or forefront of the foot) • Bar directly over arch of foot.	• Weight distribution on mid foot (i.e. no visible raising of heel or forefront of the foot) • Bar directly over arch of foot. • Feet parallel to one another.
Variable Components			
• Bar height • Displacement of lifter under the bar. • Foot position (i.e width and angle)	• Height of receive.	• Bar height • Foot position (i.e width and angle)	• Foot position (i.e width and angle)
Positional Video Capture			
• Frame in which the bar is "motionless"	• Frame prior to which the bar begins to deform if heavy enough.	• Frame at which the lifter is at their lower point in the squat position.	• Frame at which the lifter is motionless with the bar fixed in front rack (clean) or overhead (snatch)

a = 45 degree capture; b = sagittal plane capture.

Table 2. Components of the transition to the recovery.

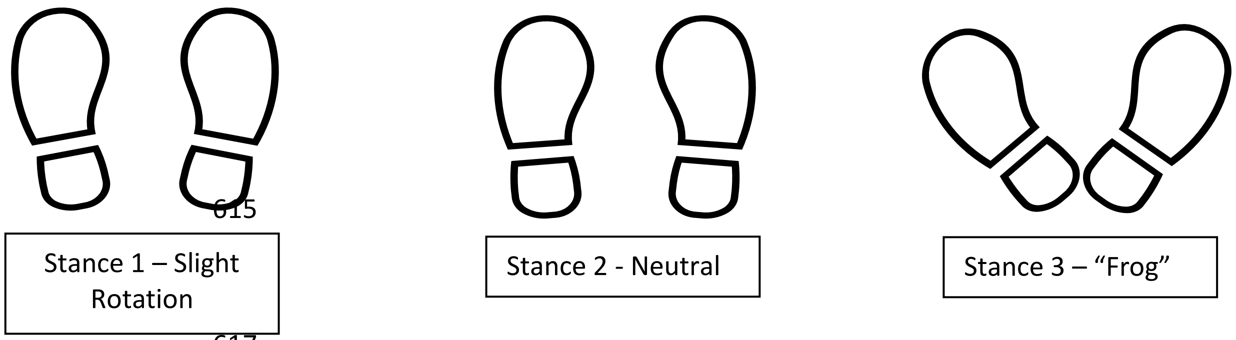

Figure 1 – General adopted foot positions during the set.

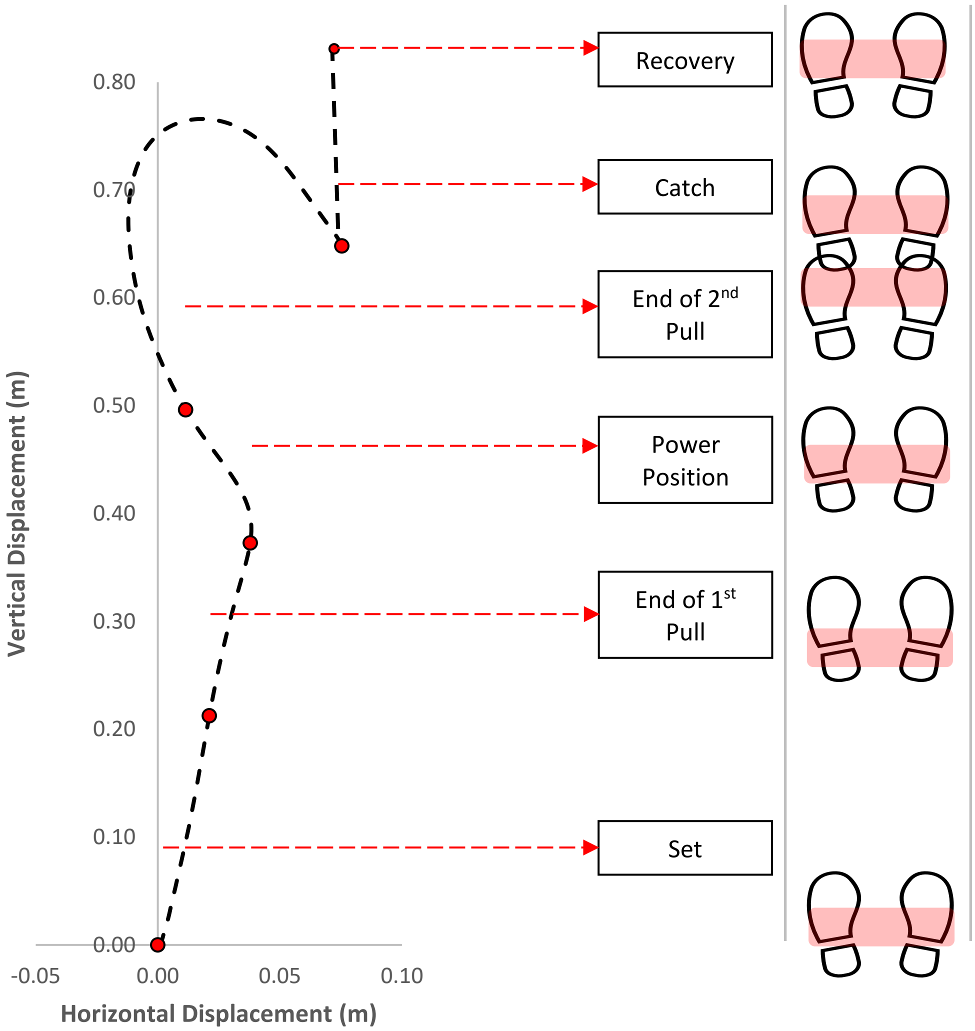

Figure 2 – Barbell trajectory and centre of pressure distribution at each phase.

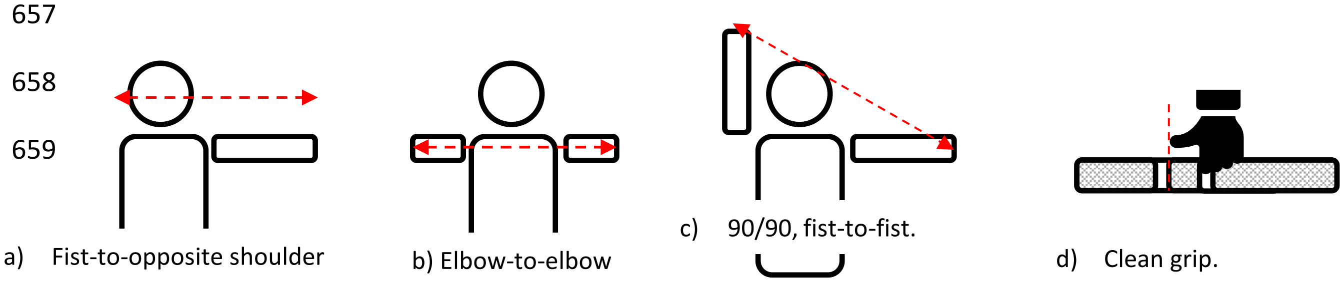

Figure 3 – Determining grip width for the snatch (a -c) and clean (d).

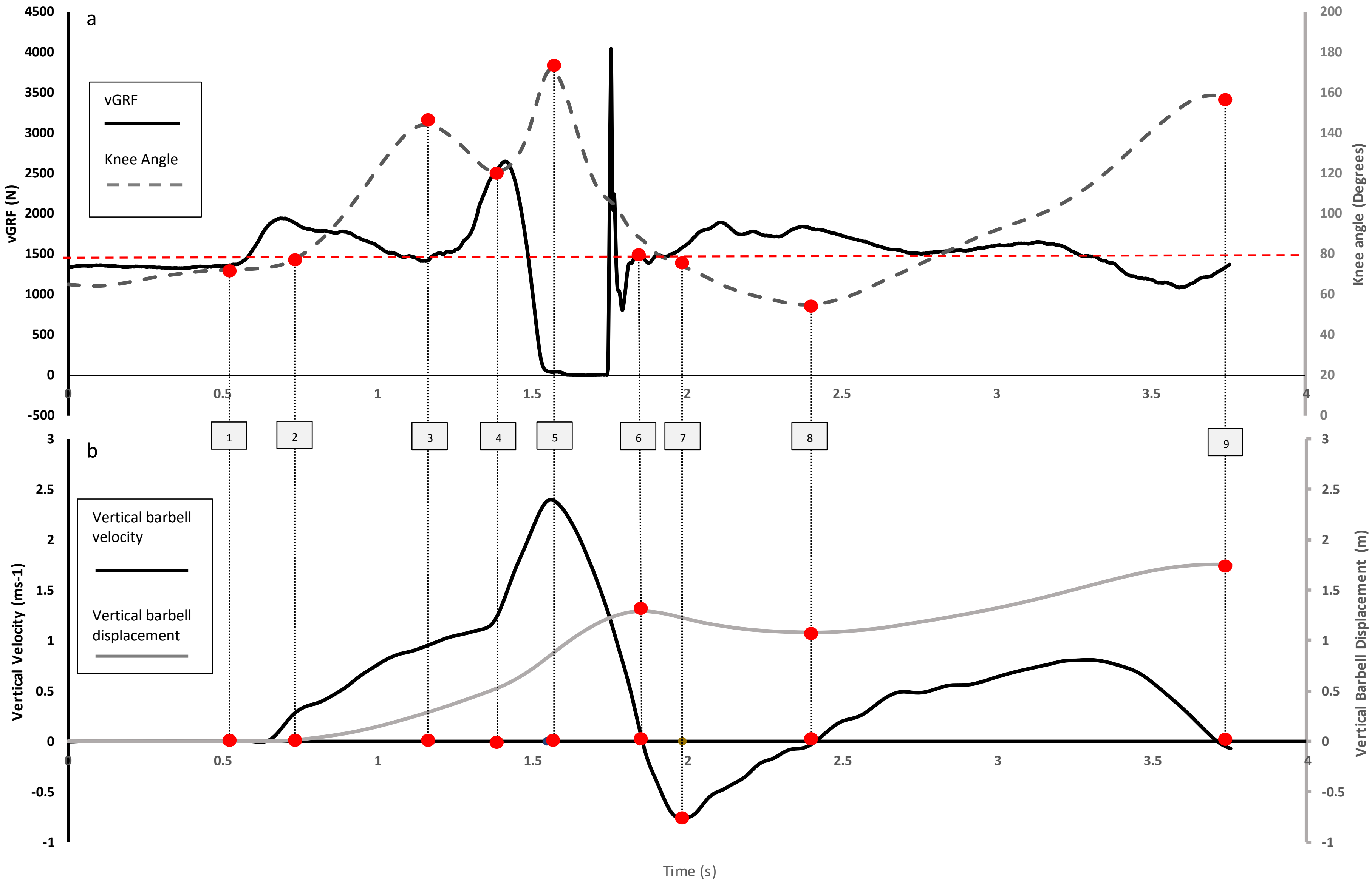
a
vGRF
Knee Angle
vGRF (N)
Knee angle (Degrees)
b
Vertical barbell velocity
Vertical barbell displacement
Vertical Velocity (ms-1)
Vertical Barbell Displacement (m)
1
2
3
4
5
6
7
8
9
Time (s)

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Figure 4 a – Where vGRF = vertical ground reaction force, N = Newtons
Figure 4 b – Where $m \cdot s^{-1}$ = meters per second, m = meters and s = seconds.
Each value represents a key phase within the lift; 1 = gripping the bar, 2 = initiation of 1st pull (defined as point prior to when the barbell is vertically displaced), 3 = end of 1st pull (defined as 1st peak knee extension), 4 = power position (defined as 1st peak knee flexion), 5 = end of second pull (defined as 2nd peak knee extension), 6 = peak barbell height (defined as greatest vertical displacement of the barbell and when velocity = 0 $m \cdot s^{-1}$), 7 = receive (defined as minimal velocity), 8 = catch (defined as 2nd peak knee flexion and when barbell velocity = 0 $m \cdot s^{-1}$ and its vertical displacement is at its lowest) and 9 = recovery (defined when knees reach maximal extension and barbell velocity = 0 $m \cdot s^{-1}$).

1 – 2 = taking slack out the bar; 2 – 3 = 1st pull; 3 – 4 = transition; 4 – 5 = 2nd pull; 5 – 6 = turnover; 6 – 7 = receive, 7 – 8 = catch, 8 – 9 = recovery.