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# Barbell Trajectory and Kinematics during Two International Weightlifting Championships

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Barbell Trajectory and Kinematics during Two International Weightlifting Championships

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ABSTRACT

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Several methods have been used in the scientific literature to study the weightlifting pull. Broadly, these methods are used to measure kinematic or kinetic variables exhibited by the lifter, the barbell, or the lifter-barbell system. However, there is an apparent disconnect between weightlifting research and coaching practice that may reduce the perceived benefits of technique analysis among coaches and present some challenges for coaches who seek to incorporate technique analysis into their coaching practice. Differences and trends in the technique of competitive weightlifting performances are apparent from the available literature. However, there are also gaps in the literature due to infrequent analyses that are limited to narrow subgroups of the weightlifting population. Therefore, the purposes of this dissertation were to 1) update to the scientific knowledge of weightlifting technique and performance, 2) improve coaches' ability to conduct and interpret technique analysis, and 3) enhance transferability of weightlifting in training to improve sport performance.

A review of methods used to evaluate the weightlifting pull provides some practical guidance for coaches on the application and interpretation of weightlifting technique analysis. Video analysis is recommended as the most practicable method for coaches to implement technique analysis themselves. Methods used to study 319 lifts by women and men from two major international competitions demonstrate the feasibility and usefulness of video analysis as an inexpensive,

time-efficient, and user-friendly method for coaches to conduct reliable technique analysis. The results of this dissertation suggest that a variety of techniques can be used to achieve international weightlifting success and provide some evidence of changes in weightlifting technique since at least the mid-1980's. These results also indicate that a stereotypical technique profile among elite international weightlifters does not exist, which further support the notion that strength is a primary determinant of weightlifting ability.

# DEDICATION

To my mother, Ellyn, for your fierce compassion.

To my father, Nelson, for your quiet wisdom.

To my wife, Sarah, for your unwavering love, inspiration, and belief.

To my children, Harper, Samson, and Esther, for your past, present, and future.

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Dr. Sato, thank you for your unfiltered pursuit of excellence.

Dr. Mizuguchi, thank you for your fidelity to doing things the right way.

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Thank you to Grant Gardis for teaching me what it means to be a coach.

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# CHAPTER 1

# INTRODUCTION

Weightlifting is a popular international sport consisting of the snatch and the clean and jerk. There is also wide professional interest in the weightlifting movements among coaches due to the demonstrated efficacy of the implementation of weightlifting movements in training to improve sport performance (Chaouachi et al., 2014; Hackett, Davies, Soomro, & Halaki, 2016; Seitz, Trajano, & Haff, 2014; Tricoli, Lamas, Carnevale, & Ugrinowitsch, 2005). While there is an extensive body of research on the technical and biomechanical aspects of weightlifting, it is important to bear in mind that the purpose of technique analysis should be to improve sport performance (Lees, 2002). Indeed, from a practical standpoint, technique analysis can be useful for coaches to devise teaching and coaching frameworks and may also provide rationale to implement the weightlifting movements in training to improve sport performance, weightlifting or otherwise.

However, coaches have largely been restricted from conducting technique analysis due to financial, spatial, and temporal constraints. These barriers may reduce the perceived benefit of technique analysis among coaches and reduce the likelihood of them consulting the scientific literature. Thus, the translational impact of formal technique analysis and research may be diminished. Emerging commercial technologies that seek to leverage the capabilities of personal electronic devices show some promise to enable coaches to conduct extensive technique analysis themselves. However, the historic disconnect between research and practice may present some challenges for coaches who are inexperienced or untrained in conducting technique analysis. These challenges namely include issues of validity, reliability, and data interpretation.

While these issues do exist, one cannot negate the invaluable knowledge owed to the scientific literature. For example, the kinematic and kinetic structure of the lifter, the barbell, and the lifter-barbell system are well characterized. Such analyses often delineate the weightlifting pull into discrete phases based on the position and movement of the barbell and lifter (Akkuş, 2012; Gourgoulis et al., 2002), which can be useful to identify key moments during the lift and to understand relationships between components of the lifter-barbell system throughout the lift. Furthermore, detailed study of barbell trajectory has given rise to a classification scheme for patterns of barbell displacement that aid in the assessment of an individual's technical proficiency (Hiskia, 1997; Vorobyev, 1978).

Several notable differences and trends in these aspects are also apparent from the existing literature. For example, the rate and magnitude of knee joint rotation during different phases differ based on strength and sex (Gourgoulis et al., 2002; Gourgoulis, Aggeloussis, Kalivas, Antoniou, & Mavromatis, 2004; Harbili, 2012; Kauhanen, Häkkinen, & Komi, 1984), and some variants of the velocity-time profile are more likely based on weight category (Hiskia, 1997). Additionally, differences in the relative frequencies of barbell trajectory types are apparent between different periods of competitive weightlifting history. For example, past investigations found the type 1 and 2 trajectories were most prevalent at international competitions during the 1980's with limited observations of the type 3 trajectory (Baumann, Gross, Quade, Galbierz, & Schwirtz, 1988; Garhammer, 1989, 1990). However, Hiskia observed the type 3 trajectory to be most prevalent at several international competitions in the early 1990's (Hiskia, 1997). Subsequent studies of the 2010 World Weightlifting Championship have also found the type 3 trajectory to be more prevalent, even among gold medalists, compared to past studies (Akkuş, 2012; Harbili, 2012). Thus, it appears that weightlifting technique as assessed by barbell trajectory has changed over time. Given these apparent changes in barbell trajectory, it is important to evaluate if similar trends are present in other technical and biomechanical aspects of weightlifting performance.

Despite several notable studies, analysis of performances during international competitions are not frequently reported and have usually been limited to select groups of competitors (Akkuş, 2012; Baumann et al., 1988; Garhammer, 1981; Garhammer, 1991; Harbili, 2012; Hiskia, 1997; Musser, Garhammer, Rozenek, Crussemeyer, & Vargas, 2014; Stone, O'Bryant, Williams, Johnson, & Pierce, 1998). Changes in technique over time may also occur due to changes in contested weight categories since anthropometric profiles differ based on weight category (Ford, Detterline, Ho, & Cao, 2000; Musser et al., 2014) and differences in anthropometrics contribute to differences in barbell and lifter kinematics (Musser et al., 2014). Thus, the infrequent and narrow analysis of competitive performances presents a gap in the scientific knowledge that may reduce the accuracy of existing technical models of effective weightlifting technique and the generalizability of such models to athletes of different skill, size, sex, or ability.

Existing research provides a rich body of knowledge on weightlifting technique. However, several practical barriers may impede coaches from directly implementing or accessing technique analysis. Furthermore, the cross-sectional nature of most studies on weightlifting technique presents gaps in the literature that may reduce the applicability of research findings over time. These issues highlight that further efforts to bridge the gap between research and practice are warranted and ongoing study of weightlifting technique among a variety of athletes is necessary. It is also apparent that coaches may benefit from additional guidance on incorporating technique analysis into their everyday practice—whether applying research findings or conducting technique analysis themselves. Therefore, the purposes of this dissertation were to 1) contribute to the scientific knowledge of weightlifting technique and performance, 2) improve coaches' ability to conduct and interpret technique analysis, and 3) enhance transferability of weightlifting in training to improve sport performance.

# CHAPTER 2

# METHODS TO EVALUATE THE WEIGHTLIFTING PULL: A PRACTICAL REVIEW

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Methods to evaluate the weightlifting pull: a practical review

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**Abstract**

Several methods have been used to study the weightlifting pull. Broadly, these methods are used to measure kinematic or kinetic variables exhibited by the lifter, the barbell, or the lifter-barbell system. Coaches should understand the utility of existing methods used to analyze and delineate the WL pull in order to improve their ability to effectively implement weightlifting technique analysis, integrate and apply findings across various methods, and promote evidence-driven practices. Therefore, the objectives of this review are 1) to summarize methods used to analyze the weightlifting pull and its phases and 2) to provide practical guidance for coaches to interpret and apply weightlifting technique analysis.

## Introduction

The weightlifting (WL) movements and their derivatives form the basis of training for competitive weightlifters[1] and are commonly implemented in the resistance training of other athletes[2]. Considerable research has elucidated the kinematic and kinetic structure of the WL movements with particular focus directed toward the WL pull and examining various phases within it. The WL pull refers to the portion of the snatch or the clean in which the barbell is raised from the ground to approximately waist height[3]. Interest in the WL pull derives from application of the theoretical concepts of transfer of training[4-6] and specificity[7, 8] through utilization of WL pulling movements to improve sport performance.

Several methods have been used to study the WL pull. Broadly, these methods are used to measure kinematic or kinetic variables exhibited by the lifter, the barbell, or the lifter-barbell system. Criteria dependent on the selected method are used to delineate phases of the pull, which provide insight on qualitative and quantitative characteristics of WL technique and performance (e.g. joint displacement-time profiles, joint angular velocities). Such analyses can be used to guide exercise prescription in accordance with the principles of specificity and transfer of training.

While an extensive body of research examining WL technique exists, coaches have historically been restricted from conducting instrumented technique analysis of their athletes largely due to financial, temporal, and spatial constraints. This apparent gap between research and practice among coaches may reduce the perceived benefits of formal technique analysis and research. Conversely, burgeoning consumer-based technologies may promote the incorporation of technique analysis into one’s coaching practice. However, the validity and reliability of many of these emerging technologies are not well reported[9], and lack of training or experience may lead well-intentioned coaches to waste their efforts using errant methods.

Coaches should understand the utility of existing methods used to analyze and delineate the WL pull in order to increase their ability to effectively implement WL technique analysis, integrate and apply findings across various methods, and promote evidence-driven practices. Therefore, the purpose of this review is to improve coaches' understanding of various methods to analyze WL technique and the delineation of phases during the WL pull. The objectives of this review are 1) to summarize methods used to analyze the WL pull and its phases and 2) to provide practical guidance for coaches to interpret and apply WL technique analysis.

**Technique Analysis**

'Technique analysis' refers specifically to the systematic evaluation of sport skill performance and encompasses both descriptive and analytic goals (e.g. how movements are made, determining a movement's effectiveness or its effect on performance outcomes) ultimately to improve sport performance[10]. The kinematic and temporal features of a movement are of primary practical importance for coaches because these are visibly observable and provide a basis for instruction and immediate feedback[11]. Arend & Higgins[12] further suggest careful examination to identify 'critical features', which they define as the 'parts or phases of the movement [that] can be least modified by the performer in order to achieve the goal'. Additionally, knowledge of internal and external forces and patterns of muscle activation contribute to understanding the demands of a given technique and can inform exercise prescription. Indeed, considerable research has examined all these aspects of the WL pull, and some general features of basic technique of the WL pull are apparent from this literature.

**Basic Technique of the Weightlifting Pull**

The WL pull consists of two main phases: the first pull and the second pull. The first pull refers to the initial raising of the barbell from the platform to approximately knee height[13]. During this phase, the lifter's knees extend to a first maximum joint angle while maintaining relatively constant hip and torso angles. There is a 'transition phase' between the first and second pulls during which the lifter orients his or her torso vertically while the knees re-bend (the 'double knee bend') prior to rapid, forceful extension of the hips, knees, and ankles during the second pull. The double knee bend positions the lifter to effectively produce vertical force against the ground, increases the mechanical advantage of the hip extensors, positions the knee extensors closer to their optimal length, increases stored elastic energy, and may initiate a myotatic reflex in the knee extensors[3, 14-16].

The barbell typically maintains a constantly increasing velocity during the first pull and reaches peak velocity during the second pull (Figure 1); although, peak velocity may occur during the first pull in rare instances[17, 18]. Barbell velocity may plateau or slightly decrease during the transition phase, which may occur more commonly in taller lifters[17]. A velocity decrease during the transition phase is also more likely to occur when there is greater velocity at the end of the first pull relative to peak velocity[18-20] and may be influenced by other factors such as strength[21] and skill[14, 19, 20]. Thus, while informative, the velocity-time profile alone does not predict successful performance, and optimal profiles may differ individually.

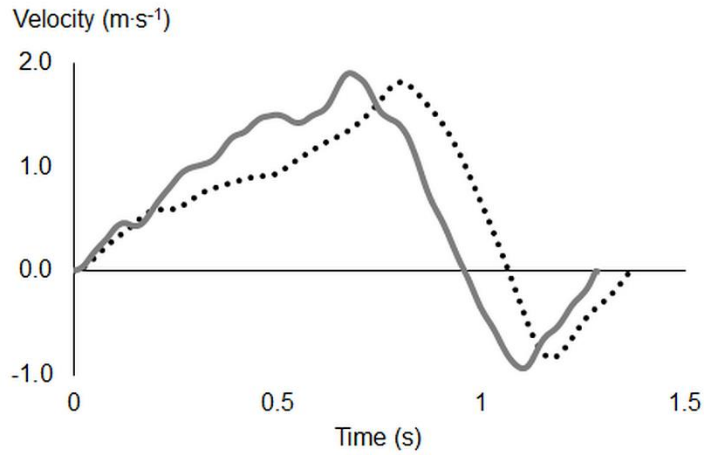


Figure 1. The barbell velocity-time profile may exhibit two maxima, each occurring during the first and second pull respectively, interceded by a plateau or slight decrease in velocity during the transition phase. Alternatively, velocity may rise continuously to a single peak.

Barbell trajectory is one of the greatest indicators of WL pull technique. Vorobyev[13] identified three basic trajectory types based on the pattern of horizontal displacement relative to the lifter and crossing of a vertical reference line drawn to intersect the center of the barbell at the start of the pull (Figure 2). Both the type 1 and 2 trajectories consist of a 'toward-away-toward' pattern with neither crossing the vertical reference line during the first 'toward' phase. The type 1 trajectory crosses the vertical reference line during the 'away' phase and may or may not cross again during the final 'toward' phase. The type 2 trajectory does not cross the vertical reference line at any point during the lift. The type 3 trajectory exhibits an 'away-toward-away-toward' pattern. The barbell typically crosses the vertical reference line during the first 'toward' phase. If the barbell crosses again during the second 'away' phase, there is a possible subsequent third crossing during the final 'toward' phase. Notably, Hiskia[17] identified a fourth trajectory type in which the barbell exhibits a 'toward-away-toward-away-toward' pattern that does not necessarily cross the vertical reference line at any instant. However, two variants of the type 4 trajectory may be observed following initial horizontal movement either toward, as during the type 1 or 2 trajectory, or away, as during the type 3 trajectory, from the lifter. As such, the type 4 trajectory may more generally be characterized as exhibiting an interceding ‘away-toward’ phase between the first ‘toward’ phase and final ‘away-toward’ phase.

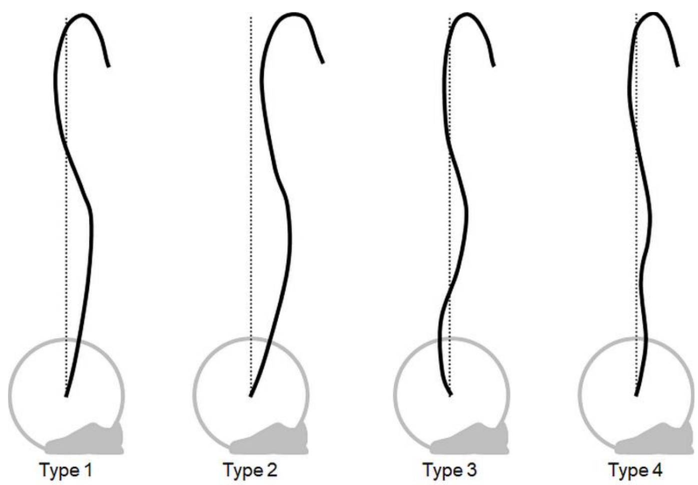


Figure 2. Barbell trajectory type is determined by the pattern of horizontal displacement relative to the lifter during the first pull and number of crossings during the second pull of a vertical reference line drawn through the center of the barbell prior to lift-off. Redrawn from Vorobyev[13] and Hiskia[17].

Observations by Hiskia[17] and Stone et al.[18] have revealed that only the type 1 trajectory necessarily crosses the vertical reference line. Vorobyev[13] initially theorized the type 1 trajectory to be the ideal pattern. However, several investigations have since found the type 2 trajectory to be more common among elite weightlifters during international competition[14, 17, 20], leading some authors to suggest the type 2 trajectory to be preferable [18, 22]. There is commonly a net rearward barbell displacement regardless of trajectory type, which is usually accompanied by the lifter jumping backward to accommodate the barbell's movement[14, 18, 20, 23-25]. Patterns of horizontal displacement are likely related to anthropometry[26] and influenced by absolute and relative strength levels[14, 18, 27]; thus, the optimal trajectory pattern may differ individually[28, 29].

The lifter experiences shifts in balance due to changes in the lifter-barbell system center of mass (COM), which is influenced by the separate movements of the lifter and barbell COMs. The center of pressure (COP) through the foot begins near the ball or arch of the foot and moves rearward during the first pull, begins to shift anteriorly toward the ball of the foot during the transition, and finally ends in front of the vertical reference line at the end of the second pull[30] (Figure 3). Changes in COP location may reflect an athlete's ability to effectively exert force against the ground throughout the pull[31]. It should be noted that COP movement during the first pull is correlated directly to the magnitude and time history of barbell horizontal displacement[30]. The anterior shift in COP after the first pull may influence the magnitude of the barbell's forward horizontal displacement during the transition phase and second pull[30]. Furthermore, barbell horizontal displacement affects muscular effort during key positions, such as at the end of the first pull and transition phase[3, 14, 30].

While these general features provide a basic template of WL technique, a survey of methods used to study the WL pull may provide additional insights to inform coaching practices. Refer to Bartonietz[19], Baumann et al.[14], Enoka[3], Hiskia[17], and Vorobyev[13] for detailed reviews of technique of the WL pull.

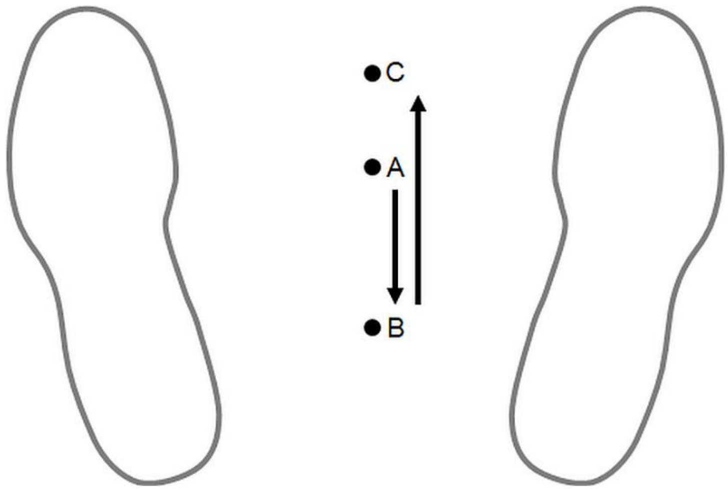


Figure 3. Center of pressure through the foot shifts anteroposteriorly during the weightlifting pull. A, balance location at lift-off; B, balance location at end of first pull; C, balance location at end of second pull. Balance locations may vary between lifts, load, and athlete. Mediolateral position not represented in figure. Redrawn and adapted from Garhammer & Taylor[30].

## Methods of Analysis

### Kinematic analysis

Kinematics is the study of motion without consideration of the forces producing or resulting from motion. Kinematic analysis involves both qualitative and quantitative approaches. These methods are used to measure or calculate variables related to the displacement, velocity, and acceleration of components of the lifter-barbell system (Table 1). Some methods of kinematic analysis have led to the delineation of several phases in addition to the first and second pull, which can be applied to both the snatch and clean. Although nomenclature and definitions may vary slightly across studies, typical phases derived from kinematic analyses are identified by changes in barbell height and direction and magnitude of knee joint rotation[13, 22, 27, 32] (Figure 4), with some studies also identifying features from the velocity- or acceleration-time profiles that coincide with the start and end points of some phases[17]. Additionally, many studies examine the snatch or clean in their entirety and so include phases that extend beyond the lifter's final extension during the second pull.

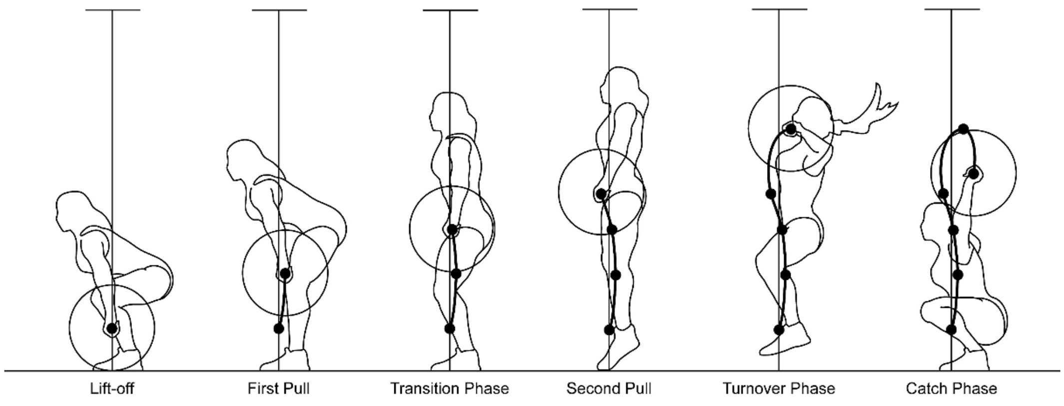


Figure 4. Although the snatch is depicted here, phases of both the snatch and clean can be determined by changes in barbell height and magnitude and direction of knee joint rotation. First pull, from lift-off until the first maximum knee extension; transition phase, from the end of the first pull until the second minimum knee angle; second pull, from the end of the transition phase until the second maximum knee angle; turnover phase, from the end of the second pull until maximum barbell height; and catch phase, from maximum barbell height until stabilization in the catch position[32].

Table 1

*Methods of Kinematic Analysis*

| Method | Component evaluated | Measurement | Primary measured or calculated variable(s) of interest |
|---|---|---|---|
| 3D MOCAP | Lifter, barbell, lifter-barbell system | Lifter: segment linear displacement; joint angular displacement<br>Barbell: linear displacement | Lifter: joint range of motion; segment displacement; segment/joint angular velocity; change in segment angle; center of mass location<br>Barbell: vertical and horizontal displacement; vertical velocity; vertical and resultant acceleration; center of mass location<br>Lifter-barbell system: center of mass location |
| Film/video analysis | Lifter, barbell | Lifter: joint angle; segment angle relative to vertical or horizontal<br>Barbell: linear displacement | Lifter: joint range of motion; segment displacement; segment/joint angular velocity; change in segment angle<br>Barbell: vertical and horizontal displacement; vertical velocity; vertical and resultant acceleration |
| LPT | Barbell | Linear displacement | Single LPT: vertical displacement<br>Dual LPT: vertical and horizontal displacement; vertical axis rotation |
| Accelerometer/IMU | Barbell | Linear acceleration | Vertical and resultant acceleration; vertical velocity |

3D MOCAP, three-dimensional motion capture; IMU, inertial measurement unit; LPT, linear position transducer

**Three-dimensional motion capture.** Three-dimensional (3D) motion capture (MOCAP) typically uses an arrangement of multiple infrared cameras to record movement of reflective markers within an established 3D reference frame. Markers are placed to measure displacement of the barbell and joints or body segments of interest. 3D MOCAP is considered the gold standard of motion analysis with accuracy of some systems reported to be 0.058 to 0.068 mm[33] (95% confidence interval), mean absolute error < 0.5 mm[34], and negligible system variability given proper calibration and procedures[35]. However, 3D MOCAP is uncommon outside of laboratory settings due to the exorbitant cost of equipment and complexity of data collection, processing, and analysis. Despite these practical limitations, the impeccable accuracy of 3D MOCAP in measuring displacement allows for extremely precise calculation of the (linear or angular) velocity or acceleration of the object(s) of interest through the single or double differentiation of the displacement-time data, respectively. Thus, 3D MOCAP allows comprehensive profiling of the displacement, velocity, and acceleration histories of various components of the lifter-barbell system. Additionally, when coupled with direct measurements of force, advanced processing of 3D MOCAP data enables complex biomechanical analysis such as inverse dynamics, which is discussed further in the section 'Kinetic Analysis'. Markerless systems have recently entered the market but currently lack the accuracy of traditional marker-based systems. Refer to Robertson et al.[36] and van der Kruk and Reijne[33] for a more detailed explanation of 3D MOCAP methods and analysis.

**Film/video analysis.** Film analysis contributed greatly to early insight on WL technique due to its relative low cost and ease of data collection. A significant drawback of film analysis is manual frame-by-frame digitization of the object(s) of interest. The advent of digital video recorders eventually led to the replacement of film with digital video to record lifts. Current methods of video analysis involve specialized software that can analyze a variety of video file types and perform automatic or semi-automatic object tracking, automatic calculation of variables of interest, and export of data to a spreadsheet for further analysis. Software range in cost from free, open-source computer programs (e.g. Kinovea) and free or low-cost mobile applications (e.g. BarSense, Coach's Eye, Ubersense, WeightLifting Motion) to several thousand USD for a single license for some programs (e.g. Dartfish). Common program features include graphical overlay and annotation to highlight objects or events of interest. In addition, some programs utilize online or cloud-based systems that allow remote recording, analysis, and sharing of video files between athletes and coaches.

These technological advances and the ubiquity of video recorders make video analysis a pragmatic method of technique analysis for both research and coaching purposes. However, camera specifications and arrangement will affect the accuracy, precision, and reliability of measurements and calculations. High frame rates ($\geq$ 100 fps) are required for accurate determination of kinematic variables such as barbell displacement, velocity, and acceleration[37]. Observation of some component(s) of the lifter-barbell system may be obstructed depending on viewing angle. For example, in a side view to observe barbell trajectory, the plates will obstruct viewing of parts of the lifter's body during portions of the lift. Similarly, viewing angle can influence the accuracy of measurements such as distance or joint angle due to perspective error. Detailed treatment of these and other considerations are presented by Garhammer and Newton[37] and Payton[38].

The use of a single camera only provides one vantage point, which impacts which component(s) of the lifter-barbell system can be analyzed and permits only two-dimensional (2D) analysis. 2D analysis of linear displacement requires calibration of the software's distance scale using an object of known length in the same plane of the object(s) of interest. For example, the diameter of the largest plate (45 cm) nearest to the camera can be used to calibrate the distance scale when analyzing barbell displacement from a side-view.

A two-camera setup alleviates many of the limitations of single-camera methods and allows for 3D analysis. Cameras can be arranged to allow unobstructed viewing of the entire lifter-barbell system, and calibration of a 3D reference frame allows for the accurate calculation of linear and angular measurements outside the observation planes of the cameras. Both single and two-camera methods permit detailed analysis of barbell trajectory (Figure 5) and the identification of phases and subphases of the WL pull, such as those in Figure 4, to closely examine the relationships and interactions between components of the lifter-barbell system throughout the lift. However, synchronization of footage from multiple cameras requires additional equipment or data processing. Calibration procedures and data analysis are also more complex compared to typical 2D methods.

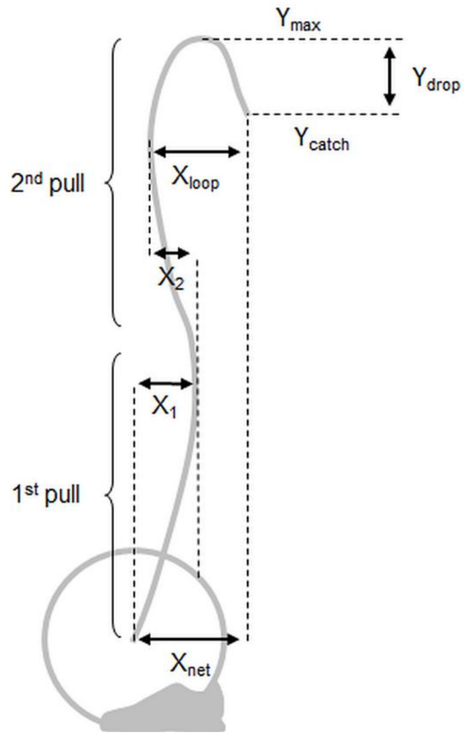


Figure 5. Several potential variables of interest can be quantified through video analysis. $X_{net}$, net horizontal displacement from start position to catch; $X_1$, horizontal displacement from start position to end of first pull; $X_2$, horizontal displacement from end of first pull to most forward position during second pull; $Y_{max}$, maximum barbell height; $Y_{catch}$, height of barbell at catch; $Y_{drop}$, difference between ($Y_{max}$ - $Y_{catch}$). Modified from Stone et al.[18]

**Linear position transducer.** Linear position transducers (LPTs) determine barbell displacement through movement of a wire that is connected to the sensor and tethered to the barbell. Measurement using a single LPT allows for one-dimensional (1D) analysis of displacement-time data and calculation of velocity and acceleration, which are both vector quantities, through the single and double differentiation of the displacement-time data, respectively. Because an LPT is only capable of measuring in one dimension, measurement error is introduced when the movement includes more than one dimension (e.g. includes both horizontal and vertical components) or the object's trajectory is not directly in line with the LPT axis. A dual-LPT setup where both LPTs are tethered to the same point on the barbell provides the ability to derive values in two dimensions through triangulation. Additionally, a system using two pairs of LPTs, with one pair attached to each side of the barbell, permits separate 2D analysis of the left and right sides of the barbell, which can differ with respect to vertical and horizontal displacement[39-41] or due to rotation around the vertical axis[39]. Refer to Westenburg et al.[42] for more information about dual-LPT setup and analysis.

**Transceiver systems.** This technology was a predecessor to modern microsensors and consumer-based software programs. One example of these systems uses an array of transceivers to transmit infrared signals to and receive ultrasonic signals from a sensor attached to the end of the barbell. Some investigators have used multiple units to analyze barbell motion bilaterally[41]. Software then computes the 3D kinematics of the end of the barbell to which the sensor is attached. This technology produces accurate data that allows the determination of barbell linear kinematic variables and the calculation of force and power. Some notable studies using this technology have contributed insight on barbell trajectory and kinematics[18], especially of lifts during international competition[17]. However, this type of transceiver system has been supplanted largely by the development of microsensors (e.g. accelerometers, inertial measurement units) and accompanying software and mobile applications. Refer to Hiskia[17] for an example of analysis conducted using a transceiver system.

**Accelerometer/inertial measurement unit.** An accelerometer is a type of microsensor that is attached or fixed to the barbell and measures changes in acceleration along a given axis. Many available devices are triaxial (i.e. 3D). However, barbell rotation during the lift changes the orientation of the sensor, and the data no longer reflect the linear movement of the barbell.

Inertial measurement units (IMUs) are accelerometers that incorporate gyroscopes to detect and correct for changes in sensor orientation making them more suitable to study the WL pull. Refer to Flores[43], Sato[44], and Wagner[45] for more information and examples on the use of accelerometers and IMUs to study the WL pull.

These devices yield acceleration-time data that can be analyzed directly and are often used to calculate velocity by single integration. Phases of positive acceleration indicate increasing velocity, while negative acceleration corresponds to decreasing velocity. Additionally, transitions in which the acceleration-time curve crosses zero indicate deflections in velocity. Positive-to-negative transitions of acceleration coincide with moving from a phase of increasing velocity to one of decreasing velocity and vice versa with negative-to-positive transitions of acceleration. Periods of zero acceleration indicate constant velocity. Furthermore, evaluation of component and resultant acceleration-time profiles may provide useful information about the nature of the lifter's application of force to the barbell[46].

**Kinetic analysis**

Kinetics is the branch of mechanics dealing with the forces and torques involved in producing or resulting from motion. Kinetic analysis includes both qualitative and quantitative approaches. In addition to the magnitude of involved forces or torques, kinetic variables of interest include impulse, power (expressed as the product of either force or torque multiplied by velocity), and rate of force or torque development (Table 2).

Although kinematics does not involve forces or torques, some kinematic measurements can be used to calculate variables such as force or power. For example, barbell displacement and velocity data can be used to calculate changes in the barbell's potential and kinetic energy (i.e. work done on the barbell), which allows the calculation of instantaneous power or average power over a given time interval such as during the first or second pull[19, 47]. Similarly, barbell acceleration can be used to calculate the barbell's force—which is also a vector quantity—using the equation for Newton's second law of motion ($\vec{F} = m \cdot \vec{a}$). This calculated force is reflective of the force imparted by the lifter onto the barbell[3]. Some of the remaining methods in this section also involve the calculation of force or torque; however, they do primarily include direct measurement of force as part of their calculations.

Table 2

*Methods of Kinetic Analysis*

| Method | Component evaluated | Measurement | Primary measured or calculated variable(s) of interest |
|---|---|---|---|
| Force plate | Lifter-barbell system | Ground reaction force | Vertical and resultant ground reaction force; rate of force development; impulse; center of pressure location |
| Inverse dynamics | Lifter, barbell, lifter-barbell system | Lifter: segment linear displacement; joint angular displacement<br>Barbell: linear displacement<br>Lifter-barbell system: vertical ground reaction force | Net and component muscle or joint forces or torques; joint power; rate of torque development |
| EMG | Lifter | Muscle activation (i.e. motor unit action potentials) | EMG signal frequency, amplitude, and rate of rise |
| ANNs | Predictive model of lifter, barbell, or lifter-barbell system | Model output of kinematic or kinetic data | Model sensitivity or accuracy (typically to assess or predict joint torque, joint angular velocity, joint range of motion) |

ANN, artificial neural network; EMG, electromyography

**Force plate.** The WL pull requires the lifter to produce vertical ground reaction force ($GRF_Z$) to perform vertical work to lift the barbell. Force plates are used to measure $GRF_Z$ using single or dual-platform arrangements. Most modern force plates contain multiple load cells, making it possible to also determine the COP. Additionally, triaxial force plates allow measurement of the resultant and component force vectors. Refer to Baumann et al.[14], Enoka[3], and Robertson et al.[36] for more information and examples of force plate analysis of the WL pull.

Unlike phases determined through kinematic analysis, force plate measurements have been used to identify phases based on changes in $GRF_Z$ relative to the system weight (i.e. total weight of the lifter and barbell load). There are two periods during which $GRF_Z$ is greater than the system weight, 'Weighting I' and 'Weighting II', and one 'Unweighting' phase during which $GRF_Z$ is less than the system weight[3]. Weighting I commences at barbell lift-off and lasts through nearly the entire first pull. Unweighting follows, beginning and ending slightly before the start and finish of the transition phase. Weighting II is the last phase and represents the final positive impulse to accelerate the barbell upward[3]. The barbell force- and acceleration-time profiles exhibit concordance with these phases[3]. Furthermore, both the barbell and $GRF_Z$ force-time profiles support the notion that the double knee bend enhances force production during the second pull[3]. Measurement of the WL pull using force plates reveals kinetic characteristics including the maximum force[3, 14, 48-50], rate of force development[14, 51-53], and impulse[3, 48-50, 53] during the WL pull. This information is useful in understanding the kinetic demands of the WL pull and the potential transfer of the WL pull to sport performance.

**Inverse dynamics.** Inverse dynamics differs from the calculation of force or power using only kinematic data. While inverse dynamics can be used to calculate 2D or 3D muscle forces or joint torques, it requires combined measurement of both kinematic (i.e.

displacement-time) and kinetic data (i.e. GRF) for these calculations. These data are then used to solve for the variable(s) of interest. Potential variables of interest in addition to muscle force[54] and joint torque[14, 55-57] include joint power[55, 58], rate of torque development[55], and whole body power[47, 59-61]. Refer to Kipp et al.[56] and Robertson et al.[36] for further discussion and examples of analysis using inverse dynamics.

Inverse dynamics is valuable to gain insight on the internal forces involved during the WL pull that would otherwise be unobservable. Practically, such information provides knowledge of the nature of muscular effort and power output during the WL pull. For example, different loads are required to produce maximum joint power at the hips, knees, and ankles[55, 58]. Additionally, inverse dynamics has been used to identify asymmetries between left and right side internal joint loads during the snatch, which coaches may be interested in to inform training and evaluate movement performance[62].

**Electromyography.** Although electromyography (EMG) measures muscle activation (i.e. motor unit action potentials), it is often combined with other techniques that directly measure force. Some researchers have demonstrated the ability to predict muscle forces using EMG during a weightlifting movement[63]. However, while EMG amplitude alone does not necessarily indicate the level of muscle force, the pattern of the EMG signal may indicate changes in activation and motor unit recruitment in muscles of interest throughout the WL pull[48, 49, 64]. EMG pattern may also indicate differences in skill level[65]. Thus, EMG studies may be used to guide exercise prescription based on patterns of muscle activation and, potentially, muscle force. Additionally, some researchers have reported differences in muscle activation patterns[66] and EMG signal[67, 68] as a result of WL training. Refer to Enoka[69], Häkkinen et al.[48], and Robertson et al.[36] for further details and examples of analysis using EMG.

**Artificial neural networks.** Artificial neural networks (ANNs) are a type of machine learning used to predict some output(s) of interest. ANNs consist of multiple nodes arranged in an input layer, one or more hidden layers, and an output layer. Information typically flows sequentially from the input layer through nodes in subsequent layers. Connections between nodes in neighboring layers comprise algorithms that use the outputs from preceding nodes to influence the interaction of subsequent nodes within the model. 'Training' of ANNs involves running multiple iterations of the model to manually tune each node or algorithm or to allow them to self-tune. Initial efforts to apply these approaches to the WL pull include qualitative assessment of lifter kinematics[70] and predicting joint torques based on lifter kinematics[71] or barbell mass and displacement data[72]. The development of robust models may allow for the accurate prediction of required muscle forces and joint torques and may contribute to the optimization of barbell and lifter kinematics. Refer to Schöllhorn[73] for a review of biomechanical applications of ANNs.

## Practical Applications

Personal electronics (e.g. smartphones, tablets, laptops) offer capable platforms for portable or microsensor technologies, mobile applications, and computer programs that broaden the coach's ability to conduct technique analysis in everyday practice. Online and cloud-based systems provide additional flexibility across multiple devices and platforms. These technologies have the potential to democratize many methods of technique analysis that were previously restricted to laboratory settings. However, coaches must be aware of the potential tradeoff between convenience and a device or software's validity and reliability[9, 74, 75]. Furthermore, some devices and software may restrict users from accessing information about how data are processed or variables are calculated, which may complicate interpretation of results. Nevertheless, some methods, such as video analysis, can be implemented immediately with personal electronics many coaches are likely to already possess and have clear guidelines to improve reliability and minimize error[37, 38]. Although coach-friendly options have practical benefits, the scientific literature remains indispensable to gain comprehensive knowledge of WL technique. Thus, coaches should have explicit knowledge of how to interpret information collected from technique analysis whether they are conducting technique analysis or consulting the literature.

Kinematic analysis has provided insight into characteristic displacement-, velocity-, and acceleration-time profiles of both the lifter and barbell during the WL pull. Notable differences in these profiles have been observed due to skill level and sex, which further supports the role of kinematic analysis in the qualitative assessment of WL pull technique and to guide coaching practice. For example, women and less-skilled athletes exhibit a slower and shallower double knee bend[21, 22, 27, 32, 49, 58, 76], which some authors have attributed to weakness in the hip and thigh musculature[14, 22, 27, 32, 76]. Thus, coaches may seek to emphasize strength development of the hip and thigh musculature in athletes from these groups. Furthermore, the delineation of phases in the WL pull also allows careful examination of the interactions that occur between components of the lifter-barbell system, especially at key positions or moments during the lift. For example, the pattern and magnitude of horizontal barbell displacement during the first pull may influence the amount of loop during the second pull[18], so coaches may choose to focus on these parameters in an effort to optimize barbell trajectory. It is also apparent that horizontal barbell displacement affects the moment arms at each joint and has a profound effect on muscular demands, especially at the knee and hip joints, and that the lengths of these moment arms should be minimized[14, 30].

Kinetic analysis provides important information on the nature of the forces required to perform the WL pull, which can also provide rationale for the implementation of the WL pull in training. Specifically, kinetic analysis can identify the contributions of individual muscle forces and joint torques to produce $GRF_Z$ and barbell or whole body power. Such information can be used to target joint specific adaptations to maximize joint torque, increase $GRF_Z$, or improve power output. Muscle activation patterns from EMG may also help to identify muscles that require special emphasis in training or that may be developed by performing the WL pull. For example, WL training produced different muscle coactivation adaptations compared to traditional resistance training and was associated with greater improvements in jump performance[66]. Furthermore, kinetic analysis in relation to specific kinematic patterns or arrangements may also reveal differences in their effectiveness, which may influence a coach's representation of idealized technique for each athlete or in general. Such analysis may contribute to optimization of barbell and lifter kinematics[71, 72, 77, 78], with the development of ANNs being potentially useful in this regard. Coaches may also wish to consider the influence of anthropometry on kinematic and kinetic aspects of WL technique[26, 79]. Furthermore, the monitoring of both kinematic and kinetic variables may be potentially useful for coaches to identify changes in skill[21, 23, 58, 62, 65, 70, 78, 80-82], fatigue[52, 70, 83], and adaptation[19, 21, 49, 66, 84, 85].

## Conclusion

Many methods have been used to conduct technique analysis of the WL pull and have contributed to an extensive knowledge of WL technique to help coaches in the conceptualization of idealized technique, the process of error correction, and the programming of training. However, coaches must consult the scientific literature to attain insight generated by several of these methods because they are generally inaccessible to coaches otherwise. Video analysis and portable or wearable devices are likely the most viable methods for the modern coach to conduct advanced technique analysis. While consumer-based technologies are aimed at providing coaches with detailed kinematic data, some of these devices may be cost prohibitive in many cases, in addition to issues of validity, reliability, and durability.

The ubiquity of digital video cameras and the availability of free or low-cost video analysis software make video analysis a readily accessible method for coaches to employ without the need to purchase additional equipment. Most current personal electronic devices have built-in high-definition video cameras with many capable of recording at 120 fps or greater, making them suitable for quantitative analysis[37]. Automated enhancement of video frame rate may improve quantitative analysis of videos recorded at < 100 fps[86, 87]. Common video analysis software features include automated object tracking, graphical overlay, and automated calculation of kinematic variables such as displacement and velocity. These features enable the coach to provide augmented visual feedback and rapid determination of kinematic variables of interest. The use of spreadsheet templates or computer scripts (e.g. R or Python programming languages) can increase the efficiency of more extensive data analysis and visualization. Thus, video analysis is a practicable method for coaches to conduct WL technique analysis.

Coaches must remain cognizant that technique is only one factor that contributes to performance outcomes. In fact, it is not unusual for the highest performers to display apparently ‘suboptimal’ technique. For example, only 3 out of 7 women snatch gold medalists from the 2010 World Weightlifting Championship displayed either of the ‘toward-away-toward’ barbell trajectory patterns[22]. Such observations highlight that coaches must be discerning about which kinematic features of the WL pull they idealize and what aspects of technique they choose to focus on when teaching or coaching. Technique analysis may also be useful to identify kinetic factors associated with producing or resulting from a given technique or movement pattern. Kinematic and kinetic analyses thus provide extensive information to characterize various components of WL pull technique. This information can be beneficial for coaches to determine effective technique, target specific movement or performance outcomes, and, ultimately, improve sport performance.

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# CHAPTER 3

# SURVEY OF BARBELL TRAJECTORY AND KINEMATICS OF THE SNATCH LIFT FROM THE 2015 WORLD AND 2017 PAN-AMERICAN WEIGHTLIFTING CHAMPIONSHIPS

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*Article*

# Survey of barbell trajectory and kinematics of the snatch lift from the 2015 World and 2017 Pan-American Weightlifting Championships

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**Abstract:** Analysis of elite performances are important to elucidate the characteristics of effective weightlifting technique at the highest level of achievement. The general technique of the weightlifting movements is well-established. However, it is also apparent that weightlifting technique can differ based on athlete characteristics. Thus, existing technical models may not accurately reflect current technique of top performers or be generalizable to athletes of different skill, size, sex, or ability. Therefore, the purpose of this study was to update the scientific knowledge of snatch technique of top international weightlifters. This study used video analysis to determine barbell trajectory and kinematics of successful snatch attempts from two major international competitions. Relative frequencies of barbell trajectory types differed based on competition, sex, category, and ranking. No statistical differences were observed among top-three performers of either sex for most kinematic variables, and there were no overall discernible patterns of effect size differences for individual or clusters of kinematic variables. Weightlifting success can be achieved with a variety of technique profiles. Strength is likely a primary determinant of weightlifting performance and ability that may also secondarily allow individuals to overcome suboptimal technique.

**Keywords:** biomechanics; technique analysis; Olympic-style lifting

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## 1. Introduction

Attempts completed during major international weightlifting competitions comprise maximum or near-maximum performances by the most-skilled performers of the weightlifting movements (the snatch, the clean, and the jerk), and these performances are instructive for the idealization of effective weightlifting technique. The general technique of the weightlifting movements is well-established [1-5]. However, it is also apparent that weightlifting technique can differ based on athlete characteristics. For example, differences in the relative frequencies of barbell trajectory types among lifters in A versus B sessions during international competitions have been observed [4,6]. Several authors have also reported differences in lifter and barbell kinematics and kinetics based on skill level [6-8]. Other investigations of competitive performances provide evidence that weightlifting technique may also be influenced by other factors such as anthropometry, weight category, and sex [4,6,9-12]. Such findings may provide some guidance to individualize teaching and coaching to best suit each athlete.

Technique differences may also be suggestive of a need for different training objectives or emphases to address deficiencies that may influence weightlifting success or sport performance. For example, some authors have suggested that the ability to execute a stretch-shortening cycle during the transition phase may be improved by increasing knee flexor concentric strength [6,8] or knee extensor eccentric strength [9,11,13]. Additionally, coaches may employ physical training to increase an athlete's speed of moving under the barbell after completing the second pull [7].

It is worth noting that the best performers may exhibit apparently suboptimal technique [9]. However, it is unclear whether top performers with suboptimal technique achieve success because of or despite their technique. Furthermore, the observed technique differences in many of the aforementioned studies are confounded by differences in weightlifting ability (i.e. absolute load lifted), and the technique an individual exhibits is partly dependent on her or his absolute and relative strength. Thus, strength is likely to be a primary determinant of weightlifting success [14].

These technique and strength differences notwithstanding, analyses of performances during major international competitions are infrequent [4,6,9,11,12,15-17] or limited to select rankings or weight categories [9,11]. Thus, existing technical models may not accurately reflect current technique of top performers or be generalizable to athletes of different skill, size, sex, or ability. Accurate technical models are important for coaches to devise frameworks for teaching and coaching the weightlifting movements. Technical and biomechanical analyses can also provide rationale for coaches to implement the weightlifting movements in training on the basis of specificity [18-20] and transference of training [21,22].

Cross-sectional analyses contribute to the cumulative scientific knowledge on weightlifting technique with the potential to inform coaching practices. Analysis of elite performances is important to elucidate the characteristics of effective weightlifting technique at the highest levels of achievement. Additionally, observed technique differences indicate the need for serial investigations encompassing multiple subgroups of performers. Therefore, the purpose of this study was to update the scientific knowledge of snatch technique of top international weightlifters. The primary aim of this study was to elucidate technical and biomechanical parameters of successful snatch attempts by lifters at the 2015 World Weightlifting Championship (WWC) and 2017 Pan-American Weightlifting Championship (PAWC).

## 2. Materials and Methods

### *2.1. Participants*

This study was an investigation of the heaviest successful snatch attempt for all athletes who lifted in the A sessions of WWC and PAWC. The heaviest successful snatch attempt by each of the top three finishers at the time of competition in each women's and men's weight category for WWC and PAWC was also identified for separate analyses. Seven women's and 8 men's weight categories were contested at WWC, and 8 weight categories each for both women and men were contested at PAWC. Three eligible attempts each from both WWC and PAWC were not recorded due to software/hardware error, so those lifters and their results were excluded from analysis. Excluded lifters included the 3rd place finisher in the women's 75 kg category from WWC and the 3rd place finisher in the women's 48 kg category from PAWC. Seven lifters from WWC and 4 lifters from PAWC did not complete any successful attempts in the snatch and were also excluded from analysis. In total, 77 women (24.1 ± 3.1 y) and 82 men (25.0 ± 3.3 y) from WWC and 75 women (25.2 ± 5.1 y) and 85 men (23.8 ± 4.2 y) from PAWC were included in this study (Tables 1 and 2). A total of 159 lifts from WWC and 160 lifts from PAWC were analyzed.

**Table 1.** Athlete characteristics for 2015 World Weightlifting Championship.

| | n | Age (y) | BW (kg) |
|---|---|---|---|
| Women | | | |
| 48 | 11 | 23.5 ± 2.7 | 47.65 ± 0.23 |
| 53 | 12 | 25.3 ± 2.8 | 52.53 ± 0.71 |
| 58 | 11 | 25.8 ± 2.5 | 57.49 ± 0.51 |
| 63 | 12 | 23.0 ± 3.2 | 62.45 ± 0.59 |
| 69 | 10 | 24.5 ± 2.7 | 68.24 ± 0.81 |
| 75 | 10 | 24.3 ± 2.3 | 74.53 ± 0.40 |
| +75 | 11 | 22.7 ± 4.1 | 114.06 ± 16.69 |
| | **77** | **24.1 ± 3.1** | **67.77 ± 21.64** |
| Men | | | |
| 56 | 7 | 24.1 ± 4.0 | 55.79 ± 0.13 |
| 62 | 11 | 25.4 ± 3.0 | 61.82 ± 0.14 |
| 69 | 11 | 24.4 ± 2.9 | 68.78 ± 0.15 |
| 77 | 11 | 24.7 ± 4.1 | 76.60 ± 0.30 |
| 85 | 10 | 24.2 ± 3.0 | 84.36 ± 0.38 |
| 94 | 10 | 25.0 ± 2.4 | 93.46 ± 0.48 |
| 105 | 10 | 24.9 ± 3.4 | 104.54 ± 0.45 |
| +105 | 12 | 26.5 ± 3.7 | 148.74 ± 6.96 |
| | **82** | **25.0 ± 3.3** | **88.76 ± 29.02** |

Values are mean ± SD; BW, bodyweight.

**Table 2.** Athlete characteristics for 2017 Pan-American Weightlifting Championship.

| | n | Age (y) | BW (kg) |
|---|---|---|---|
| Women | | | |
| 48 | 11 | 24.9 ± 4.8 | 47.67 ± 0.31 |
| 53 | 9 | 25.5 ± 6.0 | 52.35 ± 1.10 |
| 58 | 9 | 27.2 ± 5.2 | 57.44 ± 0.68 |
| 63 | 9 | 27.1 ± 5.1 | 62.70 ± 0.28 |
| 69 | 9 | 21.9 ± 3.3 | 67.89 ± 0.96 |
| 75 | 10 | 24.8 ± 4.3 | 74.58 ± 0.38 |
| 90 | 9 | 25.7 ± 6.4 | 85.58 ± 4.22 |
| +90 | 9 | 24.4 ± 5.2 | 110.01 ± 18.24 |
| | **75** | **25.2 ± 5.1** | **69.25 ± 20.07** |
| Men | | | |
| 56 | 10 | 23.2 ± 6.4 | 55.78 ± 0.23 |
| 62 | 15 | 22.5 ± 3.1 | 61.40 ± 0.60 |
| 69 | 14 | 23.8 ± 4.1 | 68.31 ± 0.62 |
| 77 | 10 | 21.4 ± 3.3 | 76.54 ± 0.56 |
| 85 | 8 | 24.3 ± 5.6 | 84.42 ± 0.43 |
| 94 | 10 | 25.4 ± 4.3 | 92.29 ± 2.62 |
| 105 | 9 | 24.7 ± 2.0 | 103.88 ± 1.22 |
| +105 | 9 | 25.8 ± 3.7 | 135.76 ± 18.17 |
| | **85** | **23.8 ± 4.2** | **81.83 ± 24.47** |

Values are mean ± SD; PAWC; BW, bodyweight.

It should also be noted that the International Weightlifting Federation changed the official women's weight categories in 2016. Thus, the women's 90 kg category from PAWC was excluded from comparative analysis, and the women's +75 category from WWC and +90 category from PAWC were considered equivalent during comparative analysis.

The ethics committee of East Tennessee State University determined this study to not be human subjects research. Therefore, subjects were not required to provide informed consent for inclusion in this study.

### *2.2. Data Collection*

Lifts were recorded at both competitions using a GoPro HERO4 Black digital video camera (San Mateo, CA, USA) in 720p resolution (1280 × 720 pixels [px]) at 240 fps. Camera setup conformed to recommendations to minimize measurement error of sagittal plane barbell kinematics [23]. The camera was arranged on a tripod 15 m and 11 m from the left edge of the competition platform at WWC and PAWC, respectively, to avoid interference with competition proceedings. The camera lens was centered and leveled 0.71 m above the competition platform surface facing in line and parallel with the platform center for both competitions.

### *2.3. Video Analysis*

Video analysis was conducted using Kinovea software (version 0.8.27). The software's working area was set to 400% zoom to improve accuracy of digitized marker placement and distance calibration. Kinovea's automatic tracking feature was used to determine barbell displacement, recorded in px, by placing a digitized marker on the center of the visible end of the barbell prior to lift-off. Raw displacement data was exported to a spreadsheet for subsequent analysis using a custom Labview program. Raw data was converted from px to cm using a respective scaling coefficient (WWC: 0.70740 $cm \cdot px^{-1}$; PAWC: 0.67497 $cm \cdot px^{-1}$) and smoothed using a 20-point moving average. Outcome variables were determined from the converted, smoothed data.

2.3.1. Calibration variability and inter-rater reliability

Scaling coefficients for WWC and PAWC were determined from 20 lifts from the respective competition using the following procedures. Ten lifts each for both women and men with at least one lift from each weight category were randomly selected. Kinovea's line tool was used to draw a line on the image along the vertical diameter of the largest plate (45 cm) nearest to the camera prior to lift-off. The length of the line was recorded in px and converted to a scaling factor (cm:px) for each file. The mean scaling factor for each set of 20 lifts were also determined. Outcome variables were determined for each file using both the original scaling factor associated with each file and the respective mean scaling factor.

The mean ± SD of calibration factors was 0.70740 ± 0.007 $cm \cdot px^{-1}$ for WWC and 0.67497 ± 0.008 $cm \cdot px^{-1}$ for PAWC (95% confidence intervals: 0.70440 to 0.71039 $cm \cdot px^{-1}$ and 0.67146 to 0.67847 $cm \cdot px^{-1}$, respectively). The 95% confidence intervals for % coefficient of variation for each set of original calibration scales was 0.6 to 1.3% for WWC and 0.8 to 1.6% for PAWC.

Repeated measures ANOVAs for each outcome variable revealed no statistical differences between methods ($F_{(1,19)} = 0.00040$ to 0.23; $p = .6$ to $> .9$ and $F_{(1,19)} = 0.0024$ to 0.14; $p = .7$ to $> .9$ for WWC and PAWC, respectively). 95% confidence intervals for Pearson's correlation coefficients for pairs of outcome variables determined from both methods were $r = 0.988$ to 0.999 and $r = 0.982$ to 0.999 for WWC and PAWC respectively ($p < .001$). 95% confidence limits of the standard error of measurement for all displacement variables ranged from a lower limit of -0.7 cm to an upper limit of 2.1 cm for WWC. For PAWC, 95% confidence limits of the standard error of the measurement for all displacement variables ranged from a lower limit of -0.8 cm to an upper limit of 2.5 cm. 95% confidence intervals for the standard error of measurement for peak vertical velocity ranged from -0.01 to 0.04 $m \cdot s^{-1}$ for WWC and -0.02 to 0.05 $m \cdot s^{-1}$ for PAWC. 95% confidence intervals for ICC reliability coefficients for the determination of all outcome variables between both methods were 0.977 to 0.999 and 0.969 to 0.999 for WWC and PAWC, respectively, based on a single measure, absolute agreement, 2-way random effects model ($p < .001$). Thus, the likely amount of error between the two methods was deemed to be negligible.

*2.4. Outcome Variables*

Barbell trajectory type was classified using definitions from Cunanan et al. [24], which are based on work by Vorobyev [5] and Hiskia [4] (Figure X). Barbell kinematic variables were modified from Stone et al. [17] and included peak vertical velocity ($V_{max}$), maximum barbell height ($Y_{max}$), height at catch ($Y_{catch}$), difference between $Y_{max}$ and $Y_{catch}$ ($Y_{drop}$), ratio of $Y_{catch}$ divided by $Y_{max}$ ($Catch_{rel}$), angle relative to vertical reference line from start position to position at $X_1$ ($\theta_1$), net horizontal displacement from start position to most rearward position during first phase of displacement toward the lifter ($X_1$), horizontal distance from $X_1$ to most anterior position between $X_1$ and $Y_{max}$ ($X_2$), horizontal distance from position at $X_2$ to position at catch ($X_{loop}$), net horizontal displacement from start position to $Y_{catch}$ ($X_{net}$) (Figure X). For determination of $Y_{drop}$ and $X_{loop}$, the catch was defined as the first instance after the phase of negative vertical velocity following $Y_{max}$ that the barbell reached a vertical velocity of 0 $m \cdot s^{-1}$.

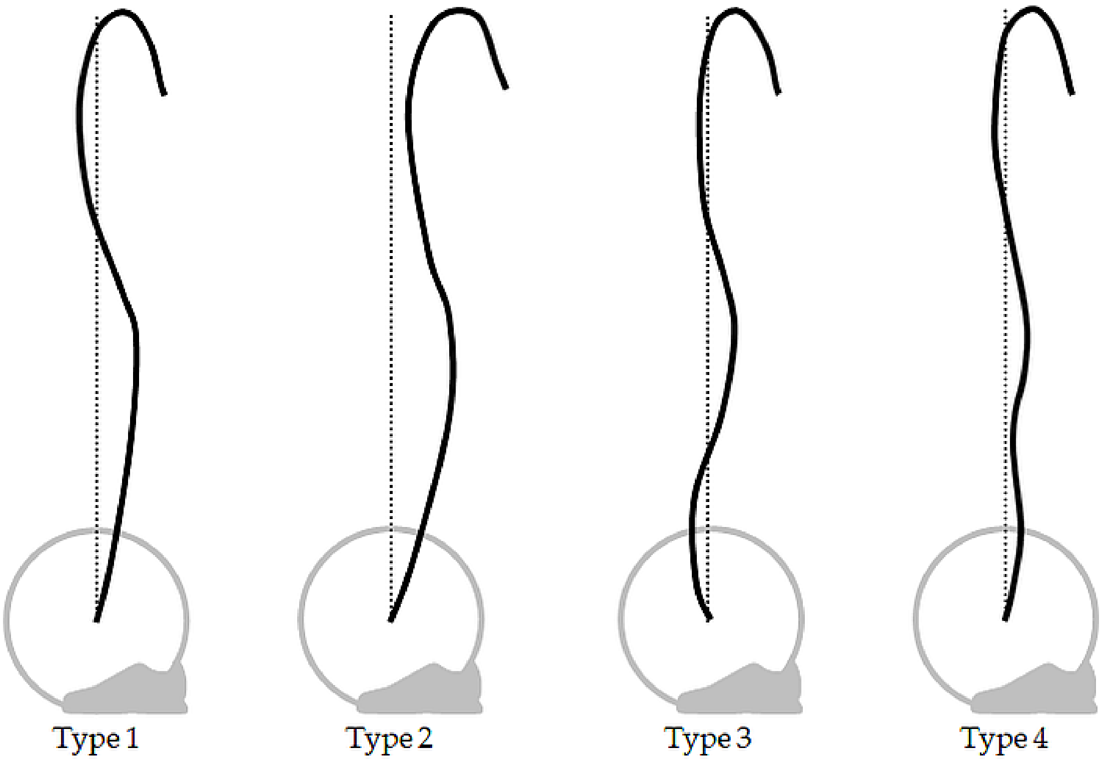


**Figure X.** Barbell trajectory types determined by pattern of horizontal displacement and crossing of vertical reference line. Figure redrawn and adapted from Vorobyev [5]and Hiskia [4].

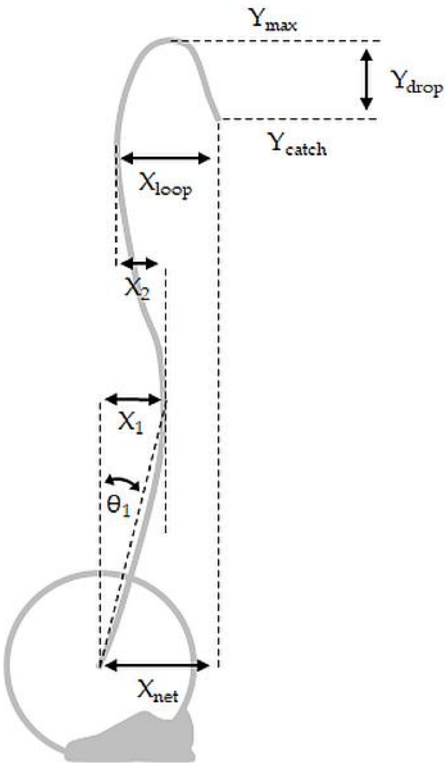


**Figure X.** Barbell kinematic variables of displacement. $Y_{max}$, maximum height; $Y_{catch}$, height at catch; $Y_{drop}$, difference between $Y_{max}$ and $Y_{catch}$; $\theta_1$, angle relative to vertical reference line from start position to $X_1$; $X_1$, net horizontal displacement from start position to most rearward position during first phase of displacement toward the lifter; $X_2$, horizontal distance from $X_1$ to most anterior position between $X_1$ and $Y_{max}$; $X_{loop}$, horizontal distance from $X_2$ to $Y_{catch}$; $X_{net}$, net horizontal displacement from start position to $Y_{catch}$. Modified and adapted from Stone et al. [17].

*2.5. Statistical Analysis*

The count and relative frequency of each barbell trajectory type was categorized by competition, sex, weight category, and continent. Descriptive statistics of each kinematic variable from all A session lifts, separated by competition, sex, and weight category, were calculated.

Separate omnibus 2x3 between-subjects ANOVAs for women and men were conducted to compare the main effects of competition (WWC, PAWC) and placement (1, 2, 3) and the interaction effect of competition and placement on each of the kinematic variables from the top-three women and men finishers from both WWC and PAWC. Assumptions of normality and homoscedasticity were assessed using Shapiro-Wilk test and Levene's test, respectively. No outliers were present in the data. In cases where assumptions of normality or homoscedasticity were violated, a robust ANOVA procedure was conducted [25]. Critical alpha was set at $\alpha$ = .05. Cohen's d effect size was calculated to evaluate the magnitude of all cell and marginal mean differences between groups.

## 3. Results

*3.1. Descriptive Analysis*

3.1.1. Barbell Trajectory

Relative frequencies of each trajectory type were similar between WWC and PAWC. Top-three finishers at WWC and PAWC exhibited some differences in relative frequencies of trajectory types compared to A session lifters within and between competitions (Tables X-X).

The type 3 trajectory was the most prevalent type among all A session lifters at both WWC and PAWC (53% and 59%, respectively), with heavier men's categories exhibiting a greater relative frequency than other categories. The type 3 trajectory was also the most common type among top-three finishers at both meets (43% and 49%, respectively); although, it was less prevalent among women compared to men at WWC (30% vs. 54%) and PAWC (43% vs. 54%). The type 2 trajectory was exhibited by approximately 30% of women and men at both WWC and PAWC. The type 1 trajectory accounted for 13% and 8% of lifts at WWC and PAWC, respectively. The type 4 trajectory occurred least frequently at both WWC and PAWC (6% and 3%, respectively).

A greater proportion of women's top-three finishers at both WWC and PAWC exhibited the type 2 trajectory compared to their A session counterparts (50% vs. 29% and 39% vs. 29%, respectively). The top-three finishers in the men's 105 and +105 categories at both WWC and PAWC exhibited the type 3 trajectory exclusively.

European top-three finishers from WWC most frequently exhibited the type 3 trajectory (57%), while Asian top-three finishers from WWC most frequently exhibited the type 2 trajectory (43%). There were no top-three finishers from North America, South America, or Africa at WWC. The type 4 trajectory accounted for 7% of the lifts among top-three finishers at WWC.

South American top-three finishers at PAWC most commonly exhibited the type 3 trajectory (55%) followed by the type 2 trajectory (38%). North American top-three finishers at PAWC had an equal distribution of type 2 and 3 trajectories (39% each) with the remainder being the type 1 trajectory (22%). No top-three finishers at PAWC exhibited the type 4 trajectory.

**Table X.** Distribution of barbell trajectory type of each athlete's heaviest successful snatch attempt in A sessions at 2015 World Weightlifting Championship.

| | **Type 1** | **Type 2** | **Type 3** | **Type 4** |
|---|---|---|---|---|
| Women | | | | |
| 48 | - | 7 (64) | 4 (36) | - |
| 53 | 1 (8) | 1 (8) | 8 (67) | 2 (17) |
| 58 | 1 (9) | 5 (45) | 5 (45) | - |
| 63 | 2 (17) | 3 (25) | 7 (58) | - |
| 69 | 1 (10) | 4 (40) | 5 (50) | - |
| 75 | 4 (40) | 1 (10) | 5 (50) | - |
| +75 | 1 (9) | 1 (9) | 9 (82) | - |
| | **10 (13)** | **22 (29)** | **43 (56)** | **2 (3)** |
| Men | | | | |
| 56 | 2 (29) | 3 (43) | 1 (14) | 1 (14) |
| 62 | 3 (27) | 6 (55) | 1 (9) | 1 (9) |
| 69 | 1 (9) | 3 (27) | 5 (45) | 2 (18) |
| 77 | 1 (9) | 5 (45) | 4 (36) | 1 (9) |
| 85 | 2 (20) | 1 (10) | 7 (70) | - |
| 94 | - | 2 (20) | 8 (80) | - |
| 105 | 1 (10) | - | 8 (80) | 1 (10) |
| +105 | - | 3 (25) | 8 (67) | 1 (8) |
| | **10 (12)** | **23 (28)** | **42 (51)** | **7 (9)** |
| Continent | | | | |
| North America | 1 (17) | 2 (33) | 3 (50) | - |
| South America | 3 (25) | 4 (33) | 4 (33) | 1 (8) |
| Asia | 6 (9) | 26 (39) | 31 (46) | 4 (6) |
| Europe | 9 (14) | 10 (15) | 43 (65) | 4 (6) |
| Africa | 1 (13) | 3 (38) | 4 (50) | - |
| **Grand Total** | **20 (13)** | **45 (28)** | **85 (53)** | **9 (6)** |

Values are count (% relative frequency).

**Table X.** Distribution of barbell trajectory type of each athlete's heaviest successful snatch attempt in A sessions at 2017 Pan-American Weightlifting Championship.

| | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Women | | | | |
| 48 | 2 (18) | 6 (55) | 2 (18) | 1 (9) |
| 53 | - | 6 (67) | 3 (33) | - |
| 58 | 2 (22) | 2 (22) | 5 (56) | - |
| 63 | 1 (11) | 3 (33) | 5 (56) | - |
| 69 | 1 (11) | 1 (11) | 6 (67) | 1 (11) |
| 75 | - | 2 (20) | 8 (80) | - |
| 90 | - | 1 (11) | 8 (89) | - |
| +90 | 3 (33) | 1 (11) | 4 (44) | 1 (11) |
| | **9 (12)** | **22 (29)** | **41 (55)** | **3 (4)** |
| Men | | | | |
| 56 | 1 (10) | 2 (20) | 7 (70) | - |
| 62 | 1 (7) | 11 (73) | 3 (20) | - |
| 69 | - | 4 (29) | 9 (64) | 1 (7) |
| 77 | - | 4 (40) | 6 (60) | - |
| 85 | 1 (13) | 2 (25) | 5 (63) | - |
| 94 | 1 (10) | 1 (10) | 8 (80) | - |
| 105 | - | 1 (11) | 8 (89) | - |
| +105 | - | - | 8 (89) | 1 (11) |
| | **4 (5)** | **25 (29)** | **54 (64)** | **2 (2)** |
| Continent | | | | |
| North America | 9 (11) | 26 (32) | 46 (56) | 1 (1) |
| South America | 4 (5) | 21 (27) | 49 (63) | 4 (5) |
| **Grand Total** | **13 (8)** | **47 (29)** | **95 (59)** | **5 (3)** |

Values are count (% relative frequency).

**Table X.** Distribution of barbell trajectory type of each top-three finisher's heaviest successful snatch attempt at 2015 World Weightlifting Championship.

| | **Type 1** | **Type 2** | **Type 3** | **Type 4** |
|---|---|---|---|---|
| Women | | | | |
| 48 | - | 2 | 1 | - |
| 53 | - | - | 1 | 2 |
| 58 | - | 2 | 1 | - |
| 63 | - | 2 | 1 | - |
| 69 | 1 | 2 | - | - |
| 75* | 1 | 1 | - | - |
| +75 | - | 1 | 2 | - |
| | **2 (10)** | **10 (50)** | **6 (30)** | **2 (10)** |
| Men | | | | |
| 56 | 1 | 1 | 1 | - |
| 62 | 2 | 1 | - | - |
| 69 | 1 | - | 1 | 1 |
| 77 | - | 1 | 2 | - |
| 85 | 1 | 1 | 1 | - |
| 94 | - | 1 | 2 | - |
| 105 | - | - | 3 | - |
| +105 | - | - | 3 | - |
| | **5 (21)** | **5 (21)** | **13 (54)** | **1 (4)** |
| Continent | | | | |
| North America | - | - | - | - |
| South America | - | - | - | - |
| Asia | 4 (13) | 13 (43) | 11 (37) | 2 (7) |
| Europe | 3 (21) | 2 (14) | 8 (57) | 1 (7) |
| Africa | - | - | - | - |
| **Grand Total** | **7 (16)** | **15 (34)** | **19 (43)** | **3 (7)** |

Values are count (% relative frequency); * one lift not recorded due to hardware/software error.

**Table X.** Distribution of barbell trajectory type of each top-three finisher's heaviest successful snatch attempt at 2017 Pan-American Weightlifting Championship.

| | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Women | | | | |
| 48* | 1 | 1 | - | - |
| 53 | - | 2 | 1 | - |
| 58 | - | 2 | 1 | - |
| 63 | 1 | 1 | 1 | - |
| 69 | 1 | - | 2 | - |
| 75 | - | 2 | 1 | - |
| 90 | - | - | 3 | - |
| +90 | 1 | 1 | 1 | - |
| | **4 (17)** | **9 (39)** | **10 (43)** | **-** |
| Men | | | | |
| 56 | - | 2 | 1 | - |
| 62 | - | 2 | 1 | - |
| 69 | - | 2 | 1 | - |
| 77 | - | 2 | 1 | - |
| 85 | 1 | - | 2 | - |
| 94 | 1 | 1 | 1 | - |
| 105 | - | - | 3 | - |
| +105 | - | - | 3 | - |
| | **2 (8)** | **9 (38)** | **13 (54)** | **-** |
| Continent | | | | |
| North America | 4 (22) | 7 (39) | 7 (39) | - |
| South America | 2 (7) | 11 (38) | 16 (55) | - |
| **Grand Total** | **6 (13)** | **18 (38)** | **23 (49)** | **-** |

Values are count (% relative frequency); * one lift not recorded due to hardware/software error.

3.1.2. Kinematic Variables

Overall, the direction of the cell mean difference of most kinematic variables from WWC and PAWC was inconsistent over weight categories for both sexes (Tables X and X). Heavier lifters tended to exhibit greater $V_{max}$, $Y_{max}$, and $Y_{catch}$, which is partly due to heavier lifters tending to also be taller [2,4,10,12]. Despite differences in $Y_{max}$ and $Y_{catch}$, $Y_{drop}$ did not exhibit an increasing or decreasing trend over weight categories for either sex. Heavier lifters also tended to exhibit greater $X_2$, which is likely partly attributable to differences in anthropometric variables among weight categories [12]. There were no discernible trends in barbell kinematics within weight categories among top-three finishers for either sex at WWC or PAWC (Tables X and X).

**Table X.** Load and kinematic variables for heaviest successful snatch attempt for A session lifters at 2015 World Weightlifting Championship.

| | Load (kg) | $V_{max}$ (m·s$^{-1}$) | $Y_{max}$ (m) | $Y_{catch}$ (m) | $Y_{drop}$ (m) | $Catch_{rel}$ (%) | $\theta_1$ (°) | $X_1$ (m) | $X_2$ (m) | $X_{loop}$ (m) | $X_{net}$ (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Women | | | | | | | | | | | |
| 48 | 82 ± 4 | 1.82 ± 0.10 | 0.89 ± 0.05 | 0.73 ± 0.04 | 0.16 ± 0.04 | 82 ± 4 | 7 ± 3 | 0.05 ± 0.02 | 0.05 ± 0.02 | 0.09 ± 0.04 | 0.09 ± 0.07 |
| 53 | 90 ± 6 | 1.81 ± 0.11 | 0.93 ± 0.05 | 0.77 ± 0.06 | 0.16 ± 0.04 | 83 ± 4 | 5 ± 3 | 0.04 ± 0.02 | 0.05 ± 0.02 | 0.10 ± 0.04 | 0.09 ± 0.06 |
| 58 | 100 ± 7 | 1.84 ± 0.13 | 0.95 ± 0.04 | 0.79 ± 0.05 | 0.17 ± 0.04 | 83 ± 4 | 7 ± 4 | 0.06 ± 0.03 | 0.05 ± 0.02 | 0.11 ± 0.04 | 0.12 ± 0.09 |
| 63 | 104 ± 7 | 1.90 ± 0.11 | 0.97 ± 0.06 | 0.81 ± 0.05 | 0.16 ± 0.03 | 83 ± 3 | 6 ± 4 | 0.06 ± 0.03 | 0.06 ± 0.03 | 0.10 ± 0.06 | 0.11 ± 0.11 |
| 69 | 112 ± 6 | 1.78 ± 0.11 | 0.98 ± 0.06 | 0.82 ± 0.06 | 0.16 ± 0.04 | 84 ± 4 | 6 ± 3 | 0.06 ± 0.03 | 0.06 ± 0.02 | 0.11 ± 0.04 | 0.12 ± 0.08 |
| 75 | 114 ± 9 | 1.88 ± 0.10 | 1.02 ± 0.05 | 0.86 ± 0.06 | 0.16 ± 0.03 | 84 ± 3 | 5 ± 2 | 0.05 ± 0.02 | 0.08 ± 0.03 | 0.09 ± 0.05 | 0.06 ± 0.10 |
| +75 | 126 ± 12 | 1.99 ± 0.11 | 1.10 ± 0.06 | 0.96 ± 0.06 | 0.15 ± 0.03 | 87 ± 2 | 7 ± 2 | 0.07 ± 0.02 | 0.07 ± 0.02 | 0.15 ± 0.05 | 0.15 ± 0.08 |
| | **104 ± 16** | **1.86 ± 0.13** | **0.98 ± 0.08** | **0.82 ± 0.09** | **0.16 ± 0.04** | **84 ± 4** | 6 ± 3 | **0.06 ± 0.03** | **0.06 ± 0.03** | **0.11 ± 0.05** | **0.10 ± 0.09** |
| Men | | | | | | | | | | | |
| 56 | 126 ± 9 | 1.79 ± 0.11 | 0.92 ± 0.07 | 0.77 ± 0.06 | 0.15 ± 0.03 | 84 ± 3 | 10 ± 5 | 0.06 ± 0.03 | 0.05 ± 0.02 | 0.08 ± 0.03 | 0.09 ± 0.05 |
| 62 | 138 ± 7 | 1.77 ± 0.07 | 0.92 ± 0.01 | 0.77 ± 0.04 | 0.15 ± 0.04 | 84 ± 4 | 7 ± 4 | 0.06 ± 0.04 | 0.05 ± 0.03 | 0.09 ± 0.07 | 0.10 ± 0.14 |
| 69 | 149 ± 8 | 1.73 ± 0.09 | 0.95 ± 0.04 | 0.79 ± 0.06 | 0.16 ± 0.04 | 83 ± 4 | 6 ± 2 | 0.05 ± 0.02 | 0.05 ± 0.02 | 0.10 ± 0.03 | 0.11 ± 0.06 |
| 77 | 162 ± 7 | 1.82 ± 0.09 | 0.99 ± 0.04 | 0.86 ± 0.04 | 0.13 ± 0.04 | 87 ± 4 | 7 ± 3 | 0.06 ± 0.02 | 0.05 ± 0.02 | 0.09 ± 0.04 | 0.10 ± 0.07 |
| 85 | 168 ± 7 | 1.83 ± 0.12 | 1.02 ± 0.05 | 0.89 ± 0.03 | 0.13 ± 0.04 | 87 ± 4 | 5 ± 1 | 0.04 ± 0.01 | 0.06 ± 0.02 | 0.09 ± 0.04 | 0.07 ± 0.07 |
| 94 | 176 ± 4 | 1.84 ± 0.10 | 1.07 ± 0.03 | 0.90 ± 0.06 | 0.17 ± 0.04 | 84 ± 4 | 5 ± 3 | 0.05 ± 0.04 | 0.07 ± 0.02 | 0.09 ± 0.03 | 0.08 ± 0.09 |
| 105 | 182 ± 6 | 1.88 ± 0.08 | 1.10 ± 0.03 | 0.93 ± 0.05 | 0.17 ± 0.03 | 84 ± 3 | 5 ± 2 | 0.05 ± 0.02 | 0.08 ± 0.02 | 0.11 ± 0.03 | 0.09 ± 0.05 |
| +105 | 196 ± 8 | 1.88 ± 0.14 | 1.17 ± 0.08 | 1.02 ± 0.07 | 0.15 ± 0.04 | 87 ± 3 | 6 ± 3 | 0.07 ± 0.03 | 0.08 ± 0.02 | 0.13 ± 0.05 | 0.12 ± 0.09 |
| | **164 ± 22** | **1.82 ± 0.11** | **1.02 ± 0.10** | **0.87 ± 0.10** | **0.15 ± 0.04** | **85 ± 4** | 6 ± 3 | **0.06 ± 0.03** | **0.06 ± 0.03** | **0.10 ± 0.05** | **0.10 ± 0.08** |

Values are mean ± SD.

**Table X.** Load and kinematic variables for heaviest successful snatch attempt for A session lifters at 2017 Pan-American Weightlifting Championship.

| | **Load (kg)** | **$V_{max}$ ($m \cdot s^{-1}$)** | **$Y_{max}$ (m)** | **$Y_{catch}$ (m)** | **$Y_{drop}$ (m)** | **$Catch_{rel}$ (%)** | **$\theta_1$ (°)** | **$X_1$ (m)** | **$X_2$ (m)** | **$X_{loop}$ (m)** | **$X_{net}$ (m)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Women | | | | | | | | | | | |
| 48 | 68 ± 10 | 1.78 ± 0.10 | 0.92 ± 0.03 | 0.77 ± 0.05 | 0.16 ± 0.03 | 83 ± 3 | 8 ± 2 | 0.06 ± 0.01 | 0.05 ± 0.02 | 0.09 ± 0.03 | 0.10 ± 0.04 |
| 53 | 83 ± 3 | 1.77 ± 0.09 | 0.93 ± 0.05 | 0.76 ± 0.06 | 0.17 ± 0.03 | 81 ± 4 | 8 ± 2 | 0.08 ± 0.02 | 0.04 ± 0.02 | 0.12 ± 0.04 | 0.16 ± 0.06 |
| 58 | 89 ± 5 | 1.89 ± 0.08 | 0.99 ± 0.02 | 0.81 ± 0.03 | 0.18 ± 0.04 | 82 ± 4 | 5 ± 2 | 0.05 ± 0.02 | 0.05 ± 0.01 | 0.10 ± 0.02 | 0.09 ± 0.04 |
| 63 | 89 ± 5 | 1.88 ± 0.08 | 1.00 ± 0.04 | 0.86 ± 0.05 | 0.14 ± 0.03 | 86 ± 3 | 7 ± 2 | 0.06 ± 0.01 | 0.05 ± 0.03 | 0.13 ± 0.06 | 0.14 ± 0.09 |
| 69 | 93 ± 9 | 1.94 ± 0.10 | 1.05 ± 0.04 | 0.86 ± 0.04 | 0.19 ± 0.04 | 82 ± 3 | 5 ± 3 | 0.05 ± 0.03 | 0.07 ± 0.03 | 0.10 ± 0.04 | 0.08 ± 0.10 |
| 75 | 99 ± 6 | 1.85 ± 0.06 | 1.05 ± 0.04 | 0.87 ± 0.07 | 0.17 ± 0.04 | 83 ± 4 | 0 ± 18 | 0.05 ± 0.03 | 0.07 ± 0.03 | 0.11 ± 0.04 | 0.09 ± 0.08 |
| 90 | 101 ± 13 | 1.83 ± 0.08 | 1.04 ± 0.03 | 0.89 ± 0.04 | 0.15 ± 0.04 | 86 ± 4 | 6 ± 5 | 0.06 ± 0.05 | 0.07 ± 0.02 | 0.12 ± 0.04 | 0.11 ± 0.10 |
| +90 | 99 ± 22 | 1.99 ± 0.12 | 1.12 ± 0.07 | 0.98 ± 0.09 | 0.14 ± 0.04 | 87 ± 4 | 8 ± 4 | 0.08 ± 0.04 | 0.08 ± 0.03 | 0.13 ± 0.05 | 0.13 ± 0.10 |
| | **90 ± 15** | **1.86 ± 0.11** | **1.01 ± 0.07** | **0.85 ± 0.09** | **0.16 ± 0.04** | **84 ± 4** | 6 ± 7 | **0.06 ± 0.03** | **0.06 ± 0.03** | **0.11 ± 0.04** | **0.11 ± 0.08** |
| Men | | | | | | | | | | | |
| 56 | 102 ± 10 | 1.77 ± 0.11 | 0.95 ± 0.07 | 0.81 ± 0.05 | 0.14 ± 0.04 | 85 ± 3 | 6 ± 3 | 0.05 ± 0.03 | 0.04 ± 0.03 | 0.11 ± 0.04 | 0.11 ± 0.09 |
| 62 | 113 ± 11 | 1.84 ± 0.16 | 0.97 ± 0.06 | 0.82 ± 0.07 | 0.14 ± 0.04 | 85 ± 4 | 9 ± 3 | 0.08 ± 0.03 | 0.03 ± 0.02 | 0.12 ± 0.06 | 0.17 ± 0.10 |
| 69 | 120 ± 16 | 1.79 ± 0.10 | 0.99 ± 0.05 | 0.85 ± 0.05 | 0.14 ± 0.04 | 86 ± 4 | 7 ± 3 | 0.07 ± 0.04 | 0.06 ± 0.04 | 0.10 ± 0.05 | 0.11 ± 0.12 |
| 77 | 145 ± 8 | 1.81 ± 0.10 | 1.02 ± 0.04 | 0.86 ± 0.03 | 0.16 ± 0.03 | 84 ± 3 | 6 ± 3 | 0.06 ± 0.04 | 0.03 ± 0.02 | 0.13 ± 0.04 | 0.16 ± 0.09 |
| 85 | 155 ± 5 | 1.78 ± 0.12 | 1.03 ± 0.04 | 0.89 ± 0.06 | 0.14 ± 0.04 | 86 ± 4 | 5 ± 2 | 0.05 ± 0.02 | 0.04 ± 0.02 | 0.13 ± 0.04 | 0.15 ± 0.06 |
| 94 | 153 ± 12 | 1.85 ± 0.09 | 1.08 ± 0.06 | 0.91 ± 0.05 | 0.17 ± 0.05 | 84 ± 4 | 5 ± 3 | 0.05 ± 0.03 | 0.05 ± 0.03 | 0.11 ± 0.05 | 0.11 ± 0.10 |
| 105 | 163 ± 11 | 1.84 ± 0.15 | 1.12 ± 0.06 | 0.97 ± 0.08 | 0.15 ± 0.03 | 86 ± 3 | 4 ± 4 | 0.04 ± 0.04 | 0.07 ± 0.02 | 0.09 ± 0.05 | 0.06 ± 0.10 |
| +105 | 165 ± 11 | 1.96 ± 0.12 | 1.20 ± 0.07 | 1.05 ± 0.06 | 0.15 ± 0.05 | 87 ± 4 | 5 ± 3 | 0.06 ± 0.03 | 0.08 ± 0.02 | 0.11 ± 0.04 | 0.09 ± 0.05 |
| | **136 ± 25** | **1.83 ± 0.13** | **1.03 ± 0.09** | **0.88 ± 0.09** | **0.15 ± 0.04** | **85 ± 4** | 6 ± 3 | **0.06 ± 0.03** | **0.05 ± 0.03** | **0.11 ± 0.05** | **0.12 ± 0.10** |

Values are mean ± SD.

**Table X.** Load and kinematic variables for heaviest successful snatch attempt for top-three women in each weight category at 2015 World Weightlifting Championship.

| | Load (kg) | $V_{max}$ ($m{\cdot}s^{-1}$) | $Y_{max}$ (m) | $Y_{catch}$ (m) | $Y_{drop}$ (m) | $Catch_{rel}$ (%) | $\theta_1$ (°) | $X_1$ (m) | $X_2$ (m) | $X_{loop}$ (m) | $X_{net}$ (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Women | | | | | | | | | | | |
| 48 | | | | | | | | | | | |
| 1 | 88 | 1.80 | 0.86 | 0.67 | 0.19 | 78 | 9 | 0.07 | 0.03 | 0.13 | 0.18 |
| 2 | 85 | 1.93 | 0.94 | 0.74 | 0.21 | 78 | 0 | 0.00 | 0.06 | 0.06 | 0.00 |
| 3 | 85 | 1.73 | 0.81 | 0.70 | 0.12 | 86 | 5 | 0.04 | 0.03 | 0.12 | 0.12 |
| 53 | | | | | | | | | | | |
| 1 | 101 | 1.61 | 0.82 | 0.66 | 0.16 | 80 | 2 | 0.01 | 0.04 | 0.18 | 0.15 |
| 2 | 96 | 1.78 | 0.88 | 0.74 | 0.15 | 83 | 2 | 0.02 | 0.07 | 0.07 | 0.02 |
| 3 | 96 | 1.68 | 0.89 | 0.70 | 0.20 | 78 | 5 | 0.04 | 0.04 | 0.08 | 0.08 |
| 58 | | | | | | | | | | | |
| 1 | 112 | 1.94 | 0.94 | 0.78 | 0.16 | 83 | 8 | 0.07 | 0.04 | 0.09 | 0.12 |
| 2 | 108 | 1.71 | 0.88 | 0.71 | 0.17 | 80 | 11 | 0.11 | 0.00 | 0.18 | 0.29 |
| 3 | 106 | 2.10 | 1.02 | 0.88 | 0.15 | 86 | 7 | 0.06 | 0.06 | 0.13 | 0.13 |
| 63 | | | | | | | | | | | |
| 1 | 113 | 1.79 | 0.92 | 0.75 | 0.17 | 82 | 7 | 0.07 | 0.03 | 0.15 | 0.18 |
| 2 | 112 | 1.74 | 0.99 | 0.82 | 0.17 | 83 | 7 | 0.07 | 0.05 | 0.11 | 0.12 |
| 3 | 112 | 1.86 | 0.94 | 0.81 | 0.14 | 86 | 9 | 0.08 | 0.06 | 0.11 | 0.12 |
| 69 | | | | | | | | | | | |
| 1 | 120 | 1.79 | 0.95 | 0.76 | 0.19 | 80 | 6 | 0.06 | 0.03 | 0.20 | 0.22 |
| 2 | 116 | 1.69 | 0.97 | 0.77 | 0.20 | 80 | 8 | 0.08 | 0.04 | 0.09 | 0.14 |
| 3 | 116 | 1.94 | 1.11 | 0.89 | 0.22 | 80 | 5 | 0.05 | 0.07 | 0.07 | 0.05 |
| 75 | | | | | | | | | | | |
| 1 | 127 | 1.94 | 0.99 | 0.86 | 0.13 | 87 | 5 | 0.05 | 0.08 | 0.09 | 0.07 |
| 2 | 125 | 1.88 | 0.98 | 0.82 | 0.16 | 84 | 7 | 0.07 | 0.02 | 0.13 | 0.18 |
| 3* | - | - | - | - | - | - | - | - | - | - | - |
| +75 | | | | | | | | | | | |
| 1 | 148 | 1.95 | 1.07 | 0.96 | 0.10 | 90 | 7 | 0.08 | 0.04 | 0.11 | 0.15 |
| 2 | 145 | 1.92 | 1.06 | 0.94 | 0.12 | 88 | 5 | 0.06 | 0.04 | 0.13 | 0.15 |
| 3 | 136 | 2.18 | 1.14 | 1.02 | 0.12 | 90 | 8 | 0.08 | 0.05 | 0.14 | 0.17 |

* Lift not recorded due to hardware/software error.

**Table X.** Load and kinematic variables for heaviest successful snatch attempt for top-three men in each weight category at 2015 World Weightlifting Championship.

| | Load (kg) | $V_{max}$ (m·s$^{-1}$) | $Y_{max}$ (m) | $Y_{catch}$ (m) | $Y_{drop}$ (m) | $Catch_{rel}$ (%) | $\theta_1$ (°) | $X_1$ (m) | $X_2$ (m) | $X_{loop}$ (m) | $X_{net}$ (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Men | | | | | | | | | | | |
| 56 | | | | | | | | | | | |
| 1 | 139 | 1.67 | 0.93 | 0.73 | 0.20 | 78 | 11 | 0.07 | 0.07 | 0.06 | 0.06 |
| 2 | 132 | 1.87 | 0.85 | 0.76 | 0.09 | 89 | 2 | 0.01 | 0.03 | 0.05 | 0.03 |
| 3 | 131 | 1.62 | 0.82 | 0.67 | 0.15 | 82 | 8 | 0.05 | 0.05 | 0.07 | 0.06 |
| 62 | | | | | | | | | | | |
| 1 | 151 | 1.68 | 0.91 | 0.72 | 0.19 | 79 | 5 | 0.04 | 0.07 | 0.01 | -0.02 |
| 2 | 150 | 1.87 | 0.93 | 0.76 | 0.17 | 82 | 12 | 0.11 | 0.01 | 0.22 | 0.32 |
| 3 | 141 | 1.72 | 0.92 | 0.81 | 0.11 | 88 | 6 | 0.05 | 0.07 | 0.05 | 0.03 |
| 69 | | | | | | | | | | | |
| 1 | 160 | 1.80 | 0.98 | 0.84 | 0.14 | 86 | 5 | 0.04 | 0.06 | 0.08 | 0.07 |
| 2 | 160 | 1.78 | 0.91 | 0.81 | 0.10 | 89 | 6 | 0.05 | 0.02 | 0.11 | 0.13 |
| 3 | 158 | 1.84 | 0.99 | 0.82 | 0.17 | 83 | 1 | 0.01 | 0.06 | 0.07 | 0.02 |
| 77 | | | | | | | | | | | |
| 1 | 175 | 1.87 | 1.03 | 0.89 | 0.15 | 86 | 8 | 0.07 | 0.05 | 0.09 | 0.11 |
| 2 | 171 | 1.85 | 1.00 | 0.86 | 0.14 | 86 | 6 | 0.05 | 0.05 | 0.08 | 0.09 |
| 3 | 167 | 1.69 | 0.94 | 0.83 | 0.11 | 88 | 3 | 0.04 | 0.03 | 0.12 | 0.13 |
| 85 | | | | | | | | | | | |
| 1 | 178 | 1.94 | 1.05 | 0.92 | 0.13 | 87 | 7 | 0.07 | 0.04 | 0.17 | 0.20 |
| 2 | 176 | 1.70 | 0.95 | 0.88 | 0.07 | 93 | 6 | 0.05 | 0.06 | 0.07 | 0.06 |
| 3 | 173 | 1.79 | 0.96 | 0.85 | 0.11 | 88 | 6 | 0.02 | 0.08 | 0.08 | 0.03 |
| 94 | | | | | | | | | | | |
| 1 | 181 | 2.02 | 1.05 | 0.96 | 0.09 | 91 | 4 | 0.04 | 0.05 | 0.08 | 0.07 |
| 2 | 180 | 1.70 | 1.01 | 0.80 | 0.21 | 79 | 5 | 0.05 | 0.05 | 0.09 | 0.08 |
| 3 | 178 | 1.95 | 1.09 | 0.89 | 0.20 | 82 | 11 | 0.12 | 0.05 | 0.12 | 0.19 |
| 105 | | | | | | | | | | | |
| 1 | 192 | 1.87 | 1.15 | 0.92 | 0.23 | 80 | 4 | 0.04 | 0.08 | 0.15 | 0.11 |
| 2 | 191 | 1.79 | 1.07 | 0.93 | 0.14 | 87 | 8 | 0.07 | 0.10 | 0.08 | 0.05 |
| 3 | 186 | 1.85 | 1.07 | 0.92 | 0.16 | 85 | 7 | 0.08 | 0.07 | 0.06 | 0.07 |
| +105 | | | | | | | | | | | |
| 1 | 211 | 1.79 | 1.14 | 0.99 | 0.15 | 87 | 8 | 0.10 | 0.08 | 0.12 | 0.14 |
| 2 | 207 | 1.95 | 1.30 | 1.17 | 0.13 | 90 | 4 | 0.06 | 0.09 | 0.09 | 0.05 |
| 3 | 203 | 1.89 | 1.09 | 1.01 | 0.08 | 93 | 1 | 0.01 | 0.10 | 0.03 | -0.05 |

**Table X.** Load and kinematic variables for heaviest successful snatch attempt for top-three women in each weight category at 2017 Pan-American Weightlifting Championship.

| | **Load (kg)** | **$V_{max}$ ($m \cdot s^{-1}$)** | **$Y_{max}$ (m)** | **$Y_{catch}$ (m)** | **$Y_{drop}$ (m)** | **$Catch_{rel}$ (%)** | **$\theta_1$ (°)** | **$X_1$ (m)** | **$X_2$ (m)** | **$X_{loop}$ (m)** | **$X_{net}$ (m)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Women | | | | | | | | | | | |
| 48 | | | | | | | | | | | |
| 1 | 77 | 1.69 | 0.92 | 0.77 | 0.15 | 84 | 6 | 0.08 | 0.00 | 0.10 | 0.17 |
| 2 | 77 | 1.63 | 0.94 | 0.79 | 0.15 | 84 | 5 | 0.05 | 0.06 | 0.04 | 0.02 |
| 3* | - | - | - | - | - | - | - | - | - | - | - |
| 53 | | | | | | | | | | | |
| 1 | 88 | 1.85 | 1.03 | 0.84 | 0.19 | 82 | 9 | 0.09 | 0.04 | 0.08 | 0.13 |
| 2 | 86 | 1.70 | 0.88 | 0.71 | 0.18 | 80 | 8 | 0.06 | 0.04 | 0.11 | 0.13 |
| 3 | 86 | 1.78 | 0.95 | 0.76 | 0.18 | 81 | 9 | 0.09 | 0.04 | 0.12 | 0.16 |
| 58 | | | | | | | | | | | |
| 1 | 94 | 1.84 | 0.97 | 0.80 | 0.17 | 83 | 9 | 0.07 | 0.06 | 0.09 | 0.10 |
| 2 | 94 | 1.85 | 1.00 | 0.82 | 0.18 | 82 | 2 | 0.02 | 0.05 | 0.12 | 0.09 |
| 3 | 93 | 1.85 | 0.98 | 0.82 | 0.15 | 85 | 7 | 0.06 | 0.05 | 0.10 | 0.11 |
| 63 | | | | | | | | | | | |
| 1 | 97 | 2.01 | 1.03 | 0.90 | 0.14 | 87 | 7 | 0.06 | 0.10 | 0.05 | 0.02 |
| 2 | 93 | 1.86 | 0.98 | 0.81 | 0.17 | 82 | 6 | 0.06 | 0.03 | 0.19 | 0.22 |
| 3 | 93 | 2.01 | 1.02 | 0.93 | 0.09 | 91 | 7 | 0.06 | 0.07 | 0.09 | 0.08 |
| 69 | | | | | | | | | | | |
| 1 | 107 | 1.85 | 0.99 | 0.78 | 0.20 | 80 | 8 | 0.08 | 0.02 | 0.18 | 0.24 |
| 2 | 100 | 1.94 | 1.04 | 0.87 | 0.17 | 84 | 3 | 0.03 | 0.08 | 0.08 | 0.03 |
| 3 | 99 | 2.00 | 1.05 | 0.88 | 0.17 | 84 | 4 | 0.03 | 0.07 | 0.08 | 0.04 |
| 75 | | | | | | | | | | | |
| 1 | 110 | 1.85 | 1.00 | 0.84 | 0.16 | 84 | -39 | 0.00 | 0.07 | 0.08 | 0.01 |
| 2 | 103 | 1.78 | 1.07 | 0.88 | 0.19 | 82 | 7 | 0.08 | 0.04 | 0.16 | 0.20 |
| 3 | 101 | 1.78 | 1.01 | 0.82 | 0.19 | 81 | 7 | 0.07 | 0.03 | 0.13 | 0.17 |
| +90 | | | | | | | | | | | |
| 1 | 120 | 2.16 | 1.24 | 1.14 | 0.10 | 92 | 7 | 0.07 | 0.10 | 0.11 | 0.09 |
| 2 | 119 | 1.86 | 1.17 | 1.02 | 0.15 | 87 | 11 | 0.15 | 0.05 | 0.24 | 0.34 |
| 3 | 118 | 1.92 | 1.11 | 0.99 | 0.11 | 90 | 6 | 0.07 | 0.08 | 0.12 | 0.11 |

* Lift not recorded due to hardware/software error.

**Table X.** Load and kinematic variables for heaviest successful snatch attempt for top-three men in each weight category at 2017 Pan-American Weightlifting Championship.

| | Load (kg) | $V_{max}$ ($m \cdot s^{-1}$) | $Y_{max}$ (m) | $Y_{catch}$ (m) | $Y_{drop}$ (m) | $Catch_{rel}$ (%) | $\theta_1$ (°) | $X_1$ (m) | $X_2$ (m) | $X_{loop}$ (m) | $X_{net}$ (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Men | | | | | | | | | | | |
| 56 | | | | | | | | | | | |
| 1 | 119 | 1.61 | 0.86 | 0.75 | 0.11 | 87 | 6 | 0.05 | 0.03 | 0.12 | 0.14 |
| 2 | 118 | 1.70 | 0.87 | 0.80 | 0.07 | 92 | 6 | 0.05 | 0.00 | 0.14 | 0.19 |
| 3 | 108 | 1.85 | 0.95 | 0.79 | 0.16 | 83 | 6 | 0.06 | 0.01 | 0.17 | 0.22 |
| 62 | | | | | | | | | | | |
| 1 | 125 | 1.71 | 0.92 | 0.81 | 0.11 | 88 | 8 | 0.07 | 0.02 | 0.13 | 0.18 |
| 2 | 124 | 1.71 | 0.91 | 0.75 | 0.15 | 83 | 11 | 0.10 | 0.03 | 0.06 | 0.13 |
| 3 | 123 | 1.85 | 0.95 | 0.78 | 0.18 | 82 | 4 | 0.03 | 0.05 | 0.04 | 0.03 |
| 69 | | | | | | | | | | | |
| 1 | 145 | 1.93 | 0.99 | 0.90 | 0.09 | 91 | 10 | 0.11 | 0.01 | 0.16 | 0.25 |
| 2 | 143 | 1.65 | 0.96 | 0.79 | 0.17 | 82 | 5 | 0.05 | 0.04 | 0.13 | 0.14 |
| 3 | 137 | 1.71 | 0.98 | 0.82 | 0.16 | 84 | 5 | 0.06 | 0.03 | 0.12 | 0.15 |
| 77 | | | | | | | | | | | |
| 1 | 162 | 2.00 | 1.02 | 0.81 | 0.20 | 80 | 8 | 0.08 | 0.01 | 0.15 | 0.22 |
| 2 | 152 | 1.69 | 0.99 | 0.84 | 0.15 | 85 | 10 | 0.11 | 0.02 | 0.14 | 0.23 |
| 3 | 151 | 1.77 | 0.95 | 0.82 | 0.13 | 86 | 8 | 0.09 | 0.01 | 0.23 | 0.31 |
| 85 | | | | | | | | | | | |
| 1 | 160 | 1.78 | 1.05 | 0.88 | 0.17 | 84 | 7 | 0.08 | 0.01 | 0.19 | 0.25 |
| 2 | 159 | 1.77 | 1.07 | 0.90 | 0.17 | 84 | 3 | 0.03 | 0.03 | 0.17 | 0.17 |
| 3 | 158 | 2.00 | 1.09 | 0.99 | 0.10 | 91 | 4 | 0.04 | 0.06 | 0.08 | 0.06 |
| 94 | | | | | | | | | | | |
| 1 | 169 | 1.93 | 1.05 | 0.89 | 0.16 | 85 | 8 | 0.08 | 0.03 | 0.11 | 0.16 |
| 2 | 166 | 1.86 | 1.07 | 0.87 | 0.20 | 82 | 4 | 0.04 | 0.02 | 0.18 | 0.20 |
| 3 | 166 | 2.01 | 1.24 | 0.99 | 0.25 | 79 | 6 | 0.06 | 0.07 | 0.05 | 0.03 |
| 105 | | | | | | | | | | | |
| 1 | 182 | 1.78 | 1.13 | 0.97 | 0.16 | 86 | 2 | 0.02 | 0.05 | 0.10 | 0.07 |
| 2 | 175 | 1.93 | 1.12 | 0.98 | 0.13 | 88 | 4 | 0.05 | 0.09 | 0.06 | 0.02 |
| 3 | 167 | 1.63 | 1.15 | 0.94 | 0.21 | 82 | 2 | 0.02 | 0.04 | 0.08 | 0.07 |
| +105 | | | | | | | | | | | |
| 1 | 178 | 2.08 | 1.21 | 1.15 | 0.06 | 95 | 2 | 0.02 | 0.07 | 0.14 | 0.09 |
| 2 | 176 | 1.78 | 1.16 | 0.99 | 0.16 | 86 | 8 | 0.09 | 0.06 | 0.07 | 0.10 |
| 3 | 175 | 1.86 | 1.13 | 0.98 | 0.15 | 87 | 5 | 0.05 | 0.10 | 0.09 | 0.04 |

*3.2. Comparative Analysis*

3.2.1. Women

$Y_{catch}$, $\theta_1$, and $X_1$ from PAC did not meet the assumption of normality (p = .01, < .001, and .005, respectively; all other p = .1 to > .9). $\theta_1$ also did not satisfy the assumption of homoscedasticity (p = .002; all other p = .1 to > .9). A statistical main effect of competition was found only for $Y_{max}$ ($\eta^2$ = 0.106; $F_{(1,34)}$ = 4.2; p = .049). $Y_{max}$ mean ± SD was 0.96 ± 0.09 m for WWC and 1.02 ± 0.08 m for PAWC (Cohen's d 95% confidence interval = -1.3 to -0.02). No statistical main or interaction effects were found for any other variable (p = .2 to > .9) (Table X). Magnitude and directionality of effect sizes varied considerably among variables (Cohen's d = -0.87 to 0.77) (Figure X).

**Table X.** Results of omnibus 2x3 between-subjects ANOVAs for women.

| | **Competition** | | | **Placement** | | | **Competition by placement** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **$\eta^2$** | **F** | **p** | **$\eta^2$** | **F** | **p** | **$\eta^2$** | **F** | **p** |
| $V_{max}$ | 0.0017 | 0.06 | .8 | 0.092 | 1.8 | .2 | 0.020 | 0.38 | .7 |
| $Y_{max}$ | 0.11 | 4.2 | .049* | 0.011 | 0.21 | .8 | 0.019 | 0.37 | .7 |
| $Y_{catch}$‡ | - | - | .3 | - | - | .4 | - | - | > .9 |
| $Y_{drop}$ | 0.0011 | 0.041 | .8 | 0.050 | 0.90 | .4 | 0.0036 | 0.066 | > .9 |
| $Catch_{rel}$ | 0.024 | 0.89 | .4 | 0.048 | 0.88 | .4 | 0.0010 | 0.018 | > .9 |
| $\theta_1$‡ | - | - | > .9 | - | - | .8 | - | - | .9 |
| $X_1$‡ | - | - | > .9 | - | - | .8 | - | - | .9 |
| $X_2$ | 0.043 | 1.6 | .2 | 0.026 | 0.48 | > .9 | 0.006 | 0.11 | .9 |
| $X_{loop}$ | 0.0059 | 0.23 | .6 | 0.025 | 0.48 | .7 | 0.090 | 1.7 | .2 |
| $X_{net}$ | 0.0045 | 0.16 | .7 | 0.018 | 0.33 | .8 | 0.032 | 0.58 | .6 |

*, statistical effect at p < .05; ‡, $\eta^2$ and F statistic were not included in robust ANOVA procedure output.

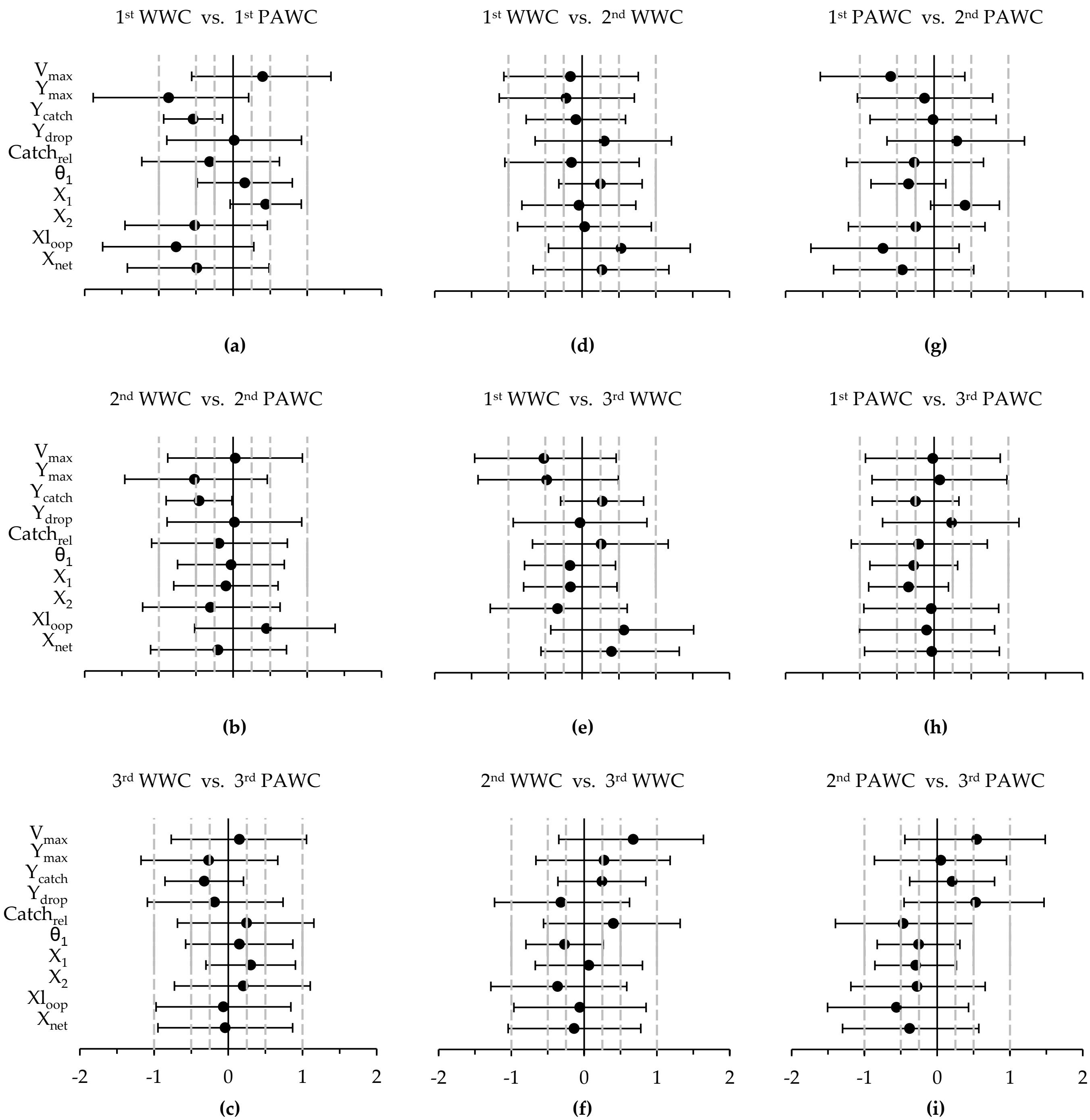


**Figure X.** Cohen's d effect size with 95% confidence interval for main effects of competition **(a-c)** and placement **(d-i)** among top-three women: **(a)** 1st place at WWC vs. 1st place at PAWC; **(b)** 2nd place at WWC vs. 2nd place at PAWC; **(c)** 3rd place at WWC vs. 3rd place at PAWC; **(d)** 1st place at WWC vs. 2nd place at WWC; **(e)** 1st place at WWC vs. 3rd place at WWC; **(f)** 2nd place at WWC vs. 3rd place at WWC; **(g)** 1st place at PAWC vs. 2nd place at PAWC; **(h)** 1st place at PAWC vs. 3rd place at PAWC; **(i)** 2nd place at PAWC vs. 3rd place at PAWC; WWC, 2015 World Weightlifting Championship; PAWC, 2017 Pan-American Weightlifting Championship.

3.2.2. Men

No variable violated assumptions of normality or homoscedasticity ($p = .1$ to $> .9$). A statistical main effect of competition was found for $X_2$ ($\eta^2 = 0.17$; $F_{(1,42)} = 8.8$; $p = .005$), $X_{loop}$ ($\eta^2 = 0.10$; $F_{(1,42)} = 5.6$; $p = .02$), and $X_{net}$ ($\eta^2 = 0.13$; $F_{(1,42)} = 6.5$; $p = .01$). Mean ± SD for $X_2$ was 0.06 ± 0.02 m for WWC and 0.04 ± 0.03 m for PAWC (Cohen's d 95% confidence interval = 0.24 to 1.48). Mean ± SD for $X_{loop}$ was 0.09 ± 0.04 m for WWC and 0.12 ± 0.05 m for PAWC (Cohen's d 95% confidence interval = -1.3 to -0.06). Mean ± SD for $X_{net}$ was 0.08 ± 0.08 for WWC and 0.14 ± 0.08 m for PAWC (Cohen's d 95% confidence interval = -1.3 to -0.13). No statistical main or interaction effects were present for any other variable ($p = .1$ to $> .9$) (Table X). Effect sizes showed considerable variation with no clear pattern within or across factor levels (Cohen's d = -1.06 to 0.68) (Figure X).

**Table X.** Results of omnibus 2x3 between-subjects ANOVAs for men.

| | **Competition** | | | **Placement** | | | **Competition by placement** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **$\eta^2$** | **F** | **p** | **$\eta^2$** | **F** | **p** | **$\eta^2$** | **F** | **p** |
| $V_{max}$ | 0.00026 | 0.01 | > .9 | 0.036 | 0.81 | .5 | 0.031 | 0.69 | .5 |
| $Y_{max}$ | 0.020 | 0.87 | .4 | 0.0059 | 0.13 | .9 | 0.021 | 0.47 | .6 |
| $Y_{catch}$ | 0.0097 | 0.45 | .5 | 0.010 | 0.24 | .8 | 0.086 | 2.0 | .1 |
| $Y_{drop}$ | 0.010 | 0.45 | .5 | 0.0046 | 0.10 | > .9 | 0.0079 | 0.17 | .8 |
| $Catch_{rel}$ | 0.0017 | 0.08 | .8 | 0.0087 | 0.20 | .8 | 0.068 | 1.5 | .2 |
| $\theta_1$ | 0.00029 | 0.01 | > .9 | 0.027 | 0.59 | .6 | 0.0049 | 0.11 | > .9 |
| $X_1$ | 0.015 | 0.66 | .4 | 0.042 | 0.94 | .4 | 0.0020 | 0.04 | > .9 |
| $X_2$ | 0.17 | 8.8 | .005* | 0.024 | 0.62 | .5 | 0.016 | 0.41 | .7 |
| $X_{loop}$ | 0.10 | 5.1 | .03* | 0.045 | 1.1 | .3 | 0.0090 | 0.22 | .8 |
| $X_{net}$ | 0.13 | 6.6 | .01* | 0.057 | 1.5 | .2 | 0.0060 | 0.16 | .9 |

*, statistical effect at p < .05.

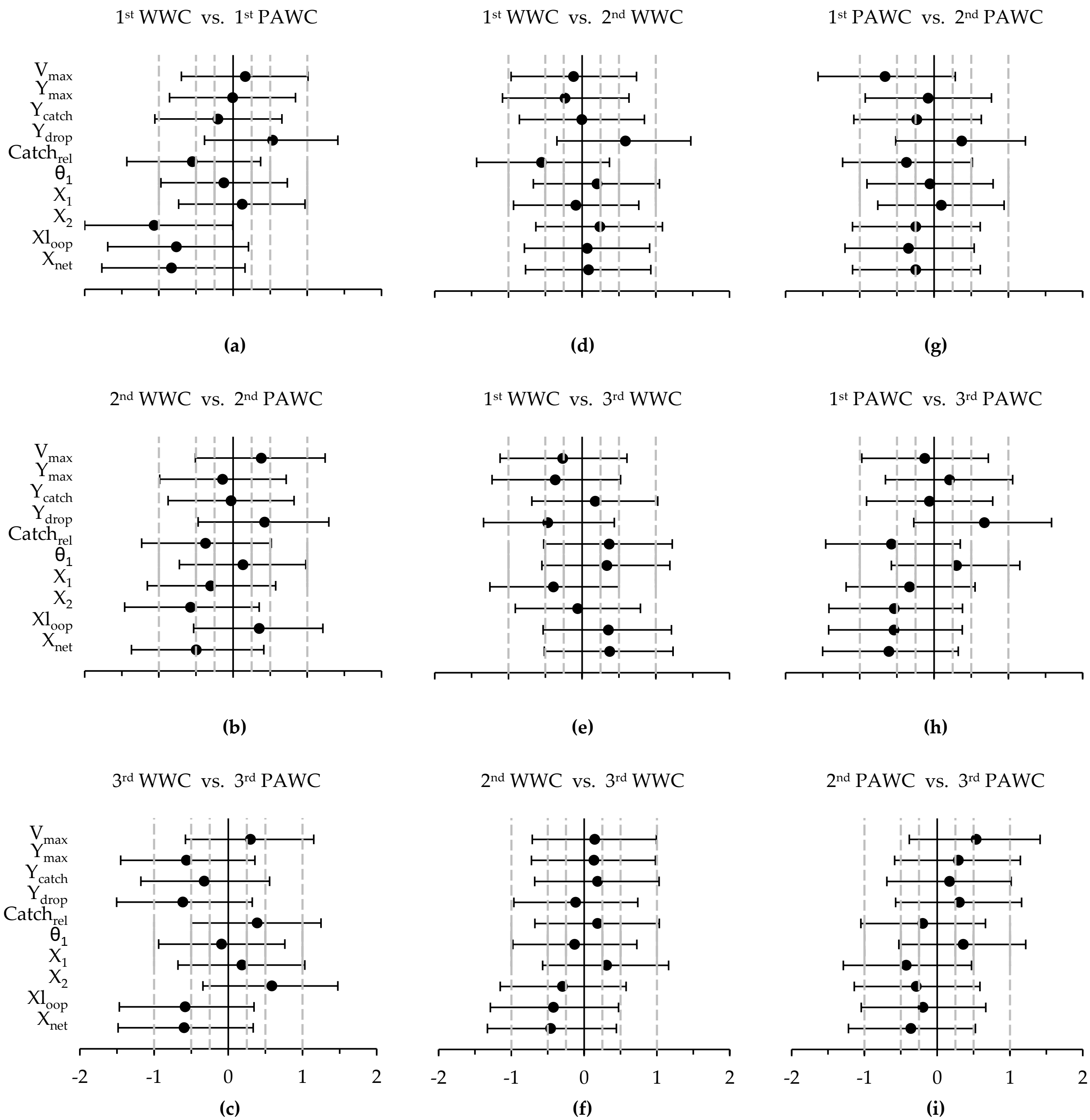


**Figure X.** Cohen's d effect size with 95% confidence interval for main effects of competition **(a-c)** and placement **(d-i)** among top-three men: **(a)** 1st place at WWC vs. 1st place at PAWC; **(b)** 2nd place at WWC vs. 2nd place at PAWC; **(c)** 3rd place at WWC vs. 3rd place at PAWC; **(d)** 1st place at WWC vs. 2nd place at WWC; **(e)** 1st place at WWC vs. 3rd place at WWC; **(f)** 2nd place at WWC vs. 3rd place at WWC; **(g)** 1st place at PAWC vs. 2nd place at PAWC; **(h)** 1st place at PAWC vs. 3rd place at PAWC; **(i)** 2nd place at PAWC vs. 3rd place at PAWC; WWC, 2015 World Weightlifting Championship; PAWC, 2017 Pan-American Weightlifting Championship.

## 4. Discussion

The aim of this study was to identify technical and biomechanical factors that might characterize successful performances of the snatch lift for elite weightlifters. This study involved 1) descriptive analysis of barbell trajectory and kinematics of the snatch lift for A session lifters at two major international competitions and 2) comparative analysis of barbell kinematics between top-three performers in the snatch lift from each meet.

The pooled relative frequencies of type 2 and 3 trajectories for women at WWC and PAWC were similar to those observed for women at the 1993 and 1994 World and European Weightlifting Championships [4]. Pooled data show that women at WWC and PAWC exhibited the type 1 trajectory less frequently (~10%) than the women included in the report by Hiskia [4]. Antoniuk et al. observed from 137 women competing at several World and European Weightlifting Championships that the type 2 trajectory was most common [26]. It is unclear in what years 2 out of the 4 competitions included in that study took place. A subsequent report by this group presented data from a total of 304 attempts by 140 women presumably from the same competitions reported in their first study that the type 1 trajectory was most common with the remainder sharing an equal distribution of type 2 and 3 trajectories [15]. Both studies reported a greater prevalence of the type 3 trajectory among the +75 category [15,26]. Pooled data for men at WWC and PAWC show similar relative frequency of the type 1 trajectory, lower relative frequency for the type 2 trajectory (~14%), and higher relative frequency for the 3 trajectory (~9%) compared to men at the 1993 and 1994 World and European Championships [4]. To the authors' knowledge, the present study is the first to quantify the prevalence of the type 4 trajectory at any competitive level; it is thus unknown how reclassification of data from prior studies to include the type 4 trajectory would affect comparison to the results of the present study.

The present results corroborate the findings of Akkuş [9] who observed that female world champions at the 2010 World Weightlifting Championship exhibited a variety of trajectory types. Musser et al. [12] found that no women snatch medalists at the 2009 Pan-American Weightlifting Championship exhibited the type 1 trajectory. However, the results of the present study demonstrate that top-three women at the Pan-American championship level can also likely exhibit a variety of trajectory types including the type 1 trajectory. The differences in relative frequencies of trajectory types between this study and previous reports [4,12,15,26] are likely due to different athlete pools, and it is unclear whether the success of certain trajectory types are exclusive to or more likely to occur in particular weight categories. However, it is likely from these differences that the relative frequencies of trajectory types observed among women at different major international competitions do vary and that high placement is not exclusive to any existing trajectory type. Although, some trajectory types may potentially be more common among top performers in some weight categories partly due to anthropometry [10,12].

Although Baumann et al. [6] did not report counts or relative frequencies of barbell trajectory type, they did indicate that 'nearly all' men in the A sessions at the 1985 World Weightlifting Championship exhibited the type 2 trajectory, with the remainder presumably exhibiting the type 1 trajectory. Baumann et al. [6] did not report any occurrences of the type 3 trajectory. Limited data from Garhammer do indicate the presence of the type 3 trajectory for the snatch and the clean among women and men world and Olympic champions during the 1980's [27,28]. However, the type 3 trajectory does not appear to have been common among top international lifters during that period [6,27]. In fact, Garhammer suggested that technique assessed by barbell trajectory had not changed from the mid-1970's to the late-1980's [27]. Subsequently, Hiskia [4] found the type 3 trajectory to be the most common among both women and men in the A sessions of the 1993 and 1994 World and European Weightlifting Championships. Data from Akkuş [9] of all women snatch gold medalists and Harbili [11] of women and men in the A session of their respective 69 kg categories at the 2010 World Weightlifting Championship indicate increased prevalence of the type 3 trajectory among top international weightlifters at that competition. Collectively, these data seem to indicate that the relative frequencies of barbell trajectory types likely vary between and within international competitions. Furthermore, the available evidence indicates a likely shift in technique among international weightlifters based on barbell trajectory.

The observed differences in the prevalence of trajectory types among top international weightlifters may reflect changes in coaching philosophy, teaching methods, and/or training methods to accommodate what have previously been considered 'suboptimal' technique (i.e. type 2 and 3 trajectories) [5,9,27]. Furthermore, the differences observed between women in this study and women in previous investigations may partially be due to the selective pressure of elite competition. Given the longer history of men's weightlifting, such selective pressure is less likely to be a factor for men currently. Kinematic differences due to body size and anthropometry [4,10,12] may also partly explain observed differences for both sexes due to periodic changes in weight categories. Serial investigations can help to delineate any apparent trends across extant cross-sectional analyses and future competitions. Furthermore, continued study of the relative frequency of trajectory types over a range of competitive levels and subgroups among them can help to identify which trajectory type(s), if any, is most characteristic of a given group.

The observations in this and recent studies [9,11] of high placing individuals at the world championship level who exhibit the type 3 trajectory is noteworthy. The type 1 trajectory was initially considered to be most favorable [5,27]. Some authors have more recently suggested the type 2 trajectory to be advantageous [17]. However, the type 3 trajectory is generally regarded to be non-beneficial and potentially detrimental [5,17] based on several biomechanical and theoretical bases. Garhammer and Taylor [29] found that anterior barbell displacement at lift-off, such as occurs with the type 3 trajectory, results in a forward shift of the lifter's center of pressure, or balance point. Such barbell displacement also increases moment arm length between the barbell center of mass and joint centers, thereby increasing joint moments and muscular forces required to lift the barbell [6]. Furthermore, anterior displacement during the first pull can increase mechanical work and decrease lift efficiency [30,31]. Thus, the prevalence of the type 3 trajectory among top-three finishers—especially among the men's 105 and +105 categories, who lifted the heaviest loads—at both WWC and PAWC emphasize the importance of high levels of absolute strength, possibly to overcome apparent technical deficiencies [17]. Greater lower limb length may also partly explain the increased prevalence of the type 3 trajectory among heavier categories [12], and anthropometric variables may partly explain differences in the prevalence of trajectory types more generally [12,32]. Nonetheless, numerous observations of the gamut of trajectory types among A session and top-three international weightlifters somewhat challenges the notion that barbell trajectory type is a useful criterion of effective weightlifting technique at this level.

Few statistical effects were observed in this study. The observed main effect of competition for $Y_{max}$ among top-three women in this study could be due to differences in stature [2,6,10,33], skill [7,8], or load lifted [33]. However, the lack of accompanying statistical or clear effect size differences for $Y_{drop}$, which has also been suggested to depend on skill [7,8], and observations of weightlifters who lifted heavier loads to greater absolute and relative vertical displacements compared to lower caliber athletes in the same weight category [8] suggest stature to be a more likely explanation of $Y_{max}$ differences observed in this study. Top-three men at WWC, who lifted the heaviest loads of any group in this study, exhibited greater $X_2$ and less $X_{net}$ and $X_{loop}$ than top-three men at PAWC. It is unlikely that greater $X_2$ itself is beneficial for performance, as greater $X_2$ would increase the overall work and energy required to complete the lift [6,34-36] and may increase instability during the catch [6]. These effects could be compounded by a potential subsequent increase of $X_{loop}$, which is likely to be less during successful attempts [17]. Greater $X_2$ among individuals of greater weightlifting ability may be consequent to the larger forces and accelerations associated with lifting heavier loads [3,6,8,14,37]. As such, it is not recommended that individuals attempt to deliberately increase $X_2$ such as by 'hipping' or swinging the bar away during the second pull [17,38]. The reduced $X_{loop}$ and $X_{net}$ among top-three men at WWC likely indicate that they jumped backward less than top-three men at PAWC. These results support the findings of Stone et al. that, while net rearward displacement is generally not detrimental or disadvantageous, smaller relative $X_{loop}$ and $X_{net}$ are likely associated with greater weightlifting success and ability [17]. Several authors have suggested that the direction of force application is important especially during the second pull [17,38,39]. The observations of reduced $X_{loop}$ and $X_{net}$ among stronger weightlifters possibly reflect these individuals' ability to produce greater vertical force and acceleration [3,6,8,36,40]. Stronger individuals are also more likely to produce faster rates of force development [41], which may improve their ability to counteract greater $X_2$ through a more effective reversal of anterior horizontal barbell acceleration during the second pull and turnover phase thereby reducing $X_{loop}$ and $X_{net}$ [38,39]. Altogether, these results suggest that greater strength may improve energy flow, force application, and vertical acceleration to favorably influence horizontal barbell kinematics that affect weightlifting performance and ability.

Studies that have identified kinematic and kinetic differences based on skill or sex have consistently identified factors that partly depend on strength [8,9,11,37]. For example, greater strength improves the ability to perform stretch-shortening cycle tasks [42-44], such as occurs during the transition phase of the weightlifting pull. Thus, strength likely mediates the rate and magnitude of knee flexion during the transition phase [9,11,13]. Several studies have also made direct comparisons between different groups of weightlifters (e.g. women vs. men [45], adolescent vs. adult [37], district vs. national/international [14]) and found overall similarity in kinematic and kinetic structure. However, when considering differences in weightlifting ability, there are notable differences in maximum ground reaction force [3,14,46], rate of force development [14,47], and absolute and relative joint and whole body power [31,37,48-50], which are all dependent on maximum strength [41]. The lifters in this study generally lifted heavier loads compared to lifters in the same or similar weight categories in previous studies [6,9,11,12,36] while exhibiting no clear differences in technique, lending further credence to the notion that strength is the primary determinant of weightlifting ability.

Indeed, there exists strong relationships between measures of maximum strength and weightlifting ability among weightlifters of a variety of competitive level. For example, Stone et al. reported Pearson's $r = 0.79$ to $0.95$ for the relationships between back squat one-repetition maximum (1RM) and snatch and clean 1RMs and Pearson's $r = 0.83$ to $0.84$ for the relationships between isometric peak force assessed using the isometric mid-thigh pull and snatch and clean 1RMs in national and international level junior and senior weightlifters from the United States [51]. Lucero et al. reported Pearson's $r = 0.91$ to $0.94$ for the relationships between self-reported back and front squat 1RMs and snatch and clean 1RMs among male competitive weightlifters in the United States [52]. Furthermore, greater strength levels may also be beneficial for the expression of other desirable physical characteristics, such as rate of force development, impulse, and power [41].

The observed variety of barbell trajectory types and overall lack of pattern among individual or clusters of kinematic variables in this study suggest no standard 'technique profile' is requisite for high achievement in weightlifting. In fact, several investigations have had limited success differentiating kinematic profiles of successful versus unsuccessful weightlifting attempts [38,39]. However, such findings should not be interpreted to suggest that technique is not an important determinant of weightlifting success at any level. Rather these findings more likely reflect the fact that the weightlifting movements are influenced by multiple degrees of freedom [17,53-55], and the varied results of this study may reflect individualized solutions to the degrees of freedom problem in weightlifting. The results of this study thus suggest the possibility of a variety of effective individualized technique profiles for weightlifting performance and ability.

It is purported that individual weightlifting technique stabilizes after only a few months of training [1]. However, the amount of intra-individual variation of lifter or barbell kinematics and kinetics during maximal attempts under competition conditions is yet to be elucidated. The results presented in two studies by Antoniuk et al., which analyzed different sets of snatch attempts from the same pool of athletes and competitions, substantiates that an individual can exhibit different barbell trajectories across attempts [15,26]. Nonetheless, the reliability of individual technique profiles is unclear. These uncertainties notwithstanding, individual technique profiles consisting of any or some technical or biomechanical parameters may potentially be useful for evaluating, monitoring, or predicting weightlifting performance and ability.

There are a variety of laboratory and field-based technologies available to conduct weightlifting technique analysis [24], and both researchers and coaches should explore the development of individual technique profiles. The methods of this study provide support for the implementation of video analysis for determining barbell kinematics and developing technique profiles. The total time to analyze a single video file including calibration during this study was less than two minutes. Use of the Kinovea's built-in graphics and analysis functions could reduce this time to 15 to 30 seconds. Additionally, Carson et al. reported a case study that demonstrate another such approach that involved long-term monitoring of lifter kinematics during an intervention intended to change weightlifting technique [56]. This case study and the anecdotal experiences of athletes and coaches highlight the complexity and difficulty of instilling changes to technique that are robust enough to persist during attempts at high relative intensities [56]. Thus, the relatively short latency of weightlifting technique stabilization and the associated challenges of technique correction underscore the importance of establishing sound technique during the earliest stages of a weightlifter's career.

Instructional and coaching methods should generally be guided by principles and tenets from the fields of biomechanics, motor learning, and physiology. While the available evidence has not identified universal optimal technique, there are general guidelines for basic weightlifting technique apparent from the extensive body of scientific literature [2-6,24]. However, coaches should consider and make appropriate accommodations for individual differences that may manifest nuances or peculiarities in technique.

## 5. Conclusions

The methods used in this study demonstrate an inexpensive, time-efficient, and user-friendly method to conduct technique analysis. The error and reliability of the methods herein can be improved by optimizing camera setup and specifications [23,35,57], controlling conditions during data collection (e.g. barbell placement [58] and lighting [59]), and selecting appropriate data smoothing or filtering techniques [59-61]. Video analysis may aid coaches in determining barbell kinematics and developing technique profiles. Such technique profiles may be useful in the evaluation, monitoring, or prediction of weightlifting performance and ability.

A variety of barbell trajectories were observed with differences based on competition, sex, category, and ranking. There was no discernible pattern of statistical or effect size differences for most of the kinematic variables observed in this study. Incidentally, the variability of individual weightlifting technique at any level requires further determination. Thus, while practically relevant, barbell trajectory or any of the examined kinematic variables alone is unlikely to reliably indicate weightlifting ability at this level. Therefore, coaches may consider evaluating weightlifting technique within a more general framework.

It seems apparent from this study's results and the available evidence that strength may be the most important determinant of weightlifting performance and ability [2,11,14,17,37,47,51,52]. It is possible that greater strength may also aid weightlifting performance by compensating for apparent technical deficiencies [17]. Thus, once an individual's technique is established, weightlifting training should primarily emphasize the development of strength and other related physical characteristics using a periodized approach [62,63] while incorporating complementary methods to refine technique [56].

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# CHAPTER 4

# SUMMARY AND FUTURE DIRECTIONS

This dissertation was designed to 1) update to the scientific knowledge of weightlifting technique and performance, 2) improve coaches' ability to conduct and interpret technique analysis, and 3) enhance transferability of weightlifting in training to improve sport performance. The methods used in this dissertation involved video recording of lifts performed during the 2015 World Weightlifting Championship (WWC) and 2017 Pan-American Weightlifting Championship (PAWC), with subsequent analysis using the free, open-source software program Kinovea (version 0.8.27) and a custom Labview program. These methods were chosen because they offer a valid, reliable, and inexpensive way to collect and analyze a large volume of data. Secondarily, these methods demonstrate a practicable method for coaches to incorporate technique analysis into their daily practice. The total time to analyze a single video file was less than 2 minutes. This process can be reduced to 15 to 30 seconds by using Kinovea's built-in graphics and analysis functions.

The heaviest successful snatch attempts by 319 weightlifters competing in the A sessions at WWC and PAWC were analyzed during this project, which is the largest sample of athletes of this caliber included in a study since 1997 (Hiskia, 1997). This dissertation builds upon the findings of previous research to conclude that weightlifting technique assessed by barbell trajectory has changed since the 1980's. Most notably, the type 3 trajectory was most commonly observed, even among top-three finishers, in the present study. These changes may reflect changes in coaching philosophy, teaching methods, and/or training methods. The results of this dissertation also suggest that the barbell kinematic variables analyzed cannot be used to reliably differentiate international weightlifters by competition or ranking. These results further suggest that optimal technique is likely individualized. Therefore, coaches may be interested in developing individual technique profiles to evaluate, monitor, or predict weightlifting performance and ability. The results of this dissertation also suggest that strength may be the primary determinant of weightlifting ability. Thus, once individual weightlifting technique is established, coaches should seek to develop maximum strength and other related characteristics using a periodized approach while incorporating complementary methods to refine technique.

It is apparent that individuals exhibit technique differences between attempts; however, the degree of intra-individual variation in weightlifting technique is unclear. Therefore, an important objective for future research is to establish the reliability of various indices of weightlifting technique for diverse samples to aid coaches in developing technique profiles. While top international weightlifters represent the most highly skilled performers of the weightlifting movements, it is also necessary to characterize weightlifting technique across a broad range of levels to better understand potential differences between levels. Thus, more research dedicated to examining weightlifting technique among different levels is needed. Although there is a high degree of similarity between the snatch and the clean, there is a lack of studies examining technical and biomechanical parameters of the clean. Direct comparison between the snatch and the clean, especially intra-individual comparison, also merits investigation. Additionally, future research can help to elucidate technical and biomechanical differences between successful and unsuccessful attempts.

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