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Enhancing Digital Video Analysis of Bar Kinematics in Weightlifting: A Case Study

Running title: Enhancing Digital Video Analysis of Weightlifting

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ABSTRACT

Weightlifting technique can be objectively assessed from two-dimensional video recordings. Despite its importance, participants' bar trajectories in research involving the snatch or clean exercises are often not reported, potentially due to the time required to digitize video. The purpose of this investigation was to evaluate the use of an LED-based marker, digital video and open source software to automatically track the bar end during weightlifting exercises. A former national-level weightlifter was recorded with a digital video camera performing the snatch, clean and jerk, and squat exercises. An LED-based marker was placed on the right end of the bar. This marker was automatically tracked using two open source software programs to obtain vertical and horizontal position coordinates. The LED-based marker was successfully auto-tracked for all videos, over a variety of camera settings. Further, the vertical and horizontal bar displacements, and vertical bar velocity were consistent between the two software programs. The present study demonstrates that an LED-based marker can be automatically tracked using open source software. This combination of an LED-based marker, consumer camera and open source software is an accessible, low cost method to objectively evaluate weightlifting technique.

INTRODUCTION

In addition to being events in competitive weightlifting, it is purported that performing the snatch, clean & jerk, and their variations will enhance performance of tasks requiring high rates of force development, such as jumping (14). The effectiveness of weightlifting exercises for this purpose may be due to the similar shape of ground reaction force pattern in weightlifting exercises and jumping (9). Specifically, a high ground reaction force impulse is generated using an inverted “U” as opposed to an inverted “V” shaped ground reaction force pattern in both exercises (9). Recently, weightlifting exercises have also been proposed as a training modality to enhance performance during impact, such as landing from a jump (21). This recommendation is due to joint kinematic and kinetic similarities between jump landings and the receiving phase of cleans and power cleans (21). Due to their potential for improving sports performance, weightlifting exercises are increasingly used in strength training programs.

The increased interest in weightlifting variations as training modalities has been accompanied by more investigations on these exercises. Although there are some general kinematic and kinetic characteristics for both the snatch and clean, variations of performing these exercises are possible, such as those distinguished by the lifters’ bar trajectory (22). The bar trajectories displayed during the snatch and clean has been found to be consistent for world and Olympic caliber weightlifters across several decades of competition. Specifically, the bar has a posterior translation during the first pull, moving towards the lifter (7, 11, 17, 24). During the second pull, the bar has a small anterior translation, moving away from the lifter (7, 11, 17, 24). Following the second pull, the bar has a second posterior translation (7, 24). The most common deviation from this characteristic bar trajectory is anterior bar translation during the first pull, which is considered a technical fault (24). This fault is often accompanied with net anterior displacement of the bar where the bar is forward of the starting

position when caught overhead or on the shoulders. Unsuccessful lifts are commonly the result of net anterior translation (24). Another key technique parameter is the height to which the bar is raised. In elite weightlifters, peak vertical bar displacement is approximately 60% and 50% of the lifter's stature for the snatch and clean, respectively (2, 23). Utilizing these parameters, researchers and coaches could objectively, rather than subjectively, evaluate an athlete's technique.

How the snatch and clean are specifically executed may influence the weight lifted, training response, and injury potential. Despite being important for interpreting results, characteristics describing an individual's technique, such as bar trajectory or peak vertical displacement, are often not reported in weightlifting research studies. Some studies report that a weightlifting coach judged the participants' technique, however, the specific technical characteristics are not detailed (e.g. 18). More often, studies do not provide any detail regarding the participants' technique, particularly in studies that investigate non-weightlifters (e.g. 14). In principle, objectively measuring technical proficiency using kinematic parameters should be feasible for both researchers and practitioners, given the availability of equipment that can be used to obtain bar displacement data.

Recent biomechanical studies have employed three-dimensional motion analysis (21) or linear position transducers (5); these technologies would allow bar kinematics to be assessed. However, these technologies require expensive equipment and specialized software that may not be available outside of a biomechanics laboratory. An alternative is digital video; the proliferation of consumer devices with digital video makes this technology widely available for both researchers and coaches. Several inexpensive or open source software programs are also available to analyze digital video (10). Some open source software programs include the capability to auto-track objects, where a pattern distinctive from the surrounding image can be tracked over multiple frames. Coloured tape and reflective markers

have been used to facilitate auto-tracking (10). However, we have found that these techniques do not create a sufficiently distinctive pattern compared to the surrounding image to be auto-tracked.

An alternative method to create a distinctive pattern is the use of light emitting diodes (LED). A benefit of LEDs is that they emit light rather than reflect it, and thus focus more energy on the camera's sensor to create a distinctive pattern. LEDs have previously been used in biomechanics research. However, these methods have required either or both specialized hardware and software, which limits their availability. The purpose of this research was to evaluate the ability to automatically track an LED-based marker recorded with digital video using open source software to assess bar kinematics in weightlifting. A specific goal was to maximize the accessibility of this method; therefore, a consumer camera, open source software, and standard spreadsheet software were used.

METHODS

Experimental approach to the problem

One participant was recorded using two-dimensional video during an exercise session. The participant performed multiple sets of the snatch, clean & jerk, and back squat as detailed in Table 1. The squat lifts were included to evaluate the applicability of the method to bar lifts other than the competition exercises in weightlifting. Bar trajectories were obtained from the digital videos using the auto-tracking function in open source software. To facilitate auto-tracking, an LED-based marker was placed on the right bar end. Different software packages, smoothing and filtering, and repeated digitizations were compared.

Table 1 about here

Subjects

One of the authors, a former Canadian national-level weightlifter, participated in the study. The lifter was 36 years old, 1.78 m tall and 115 kg body mass. His recent one repetition maximums (1 RM) were 120 kg in the snatch and 140 kg in the clean and jerk. The study was approved by a Research Ethics Board at the University of Alberta (study ID: Pro00061284).

Procedures

Digital video were recorded for all sets and repetitions performed during the exercise session. The camera was placed on a tripod to record a sagittal view at a distance of 15 m from the right end of the bar, with its optical axis 0.80 m above the ground. A Nikon D3200 camera with a 15-55 mm variable zoom lens was used in video recording mode with 1280 by 720 pixel resolution capturing 60 frames per second. The lens was set to maximum zoom and the widest aperture setting (f/5.6) was used, however, shutter speed and ISO settings were varied for purposes of evaluating the image quality (Table 1). The videos were recorded in a room with fluorescent lighting. The video data were recorded to an SD card, and later transferred to a computer for analysis.

A laboratory-constructed LED-based marker was placed on the right end of the bar (Olympic competition bar, Iron Grip, Santa Ana, CA, USA; Figure 1). The marker consisted of five evenly spaced white LEDs that were powered by two coin cell batteries. The LED-based marker was affixed to a collar made of low-temperature thermoplastic to allow the marker to be placed on and removed from the bar with ease. The entire marker and collar assembly had a mass of 37 g. A wooden rod indicating 1 m was placed in the camera's field of view for calibration purposes (Figure 2).

Figure 1 & 2 about here

One investigator performed the auto-tracking procedure for all snatch, clean and squat repetitions using the open source software programs Tracker (<http://physlets.org/tracker/>; accessed October 6, 2015) and Kinovea (www.kinovea.org; accessed October 3, 2015). For reference length calibration, the ends of the wooden rod were digitized two frames prior to lift-off. In the same frame, the coordinate system origin was assigned to the location of the LED-based marker. Positive values indicate superior and anterior with respect to the lifter. The LED-based marker was manually digitized two frames prior to lift-off, after which, the software's automatic tracking feature was used to digitize the marker until two frames past the lowest bar height in the receiving phase. Horizontal and vertical position coordinates were exported in *.xlsx file format. This procedure was performed on two separate occasions in both software programs. Two spreadsheet templates (Excel 2007, Microsoft Corporation, Redmond, WA) were developed to either smooth or filter the data. The smoothing template used a five-point moving arc to smooth position coordinates, and the first derivative of the five-point moving arc was used to calculate horizontal and vertical velocity, as described by Wood (25). The filtering template used a 4th order Butterworth filter with cut-off frequencies of 3 Hz for the horizontal (X) coordinates and 6 Hz for the vertical (Y) coordinates. These cut-offs were based on Fast Fourier transform which showed that 99% of the signal power was below these frequencies. The first derivative of the five-point moving arc was used to calculate horizontal and vertical velocity from the filtered data (25).

Peak vertical bar displacement, drop distance from peak vertical bar displacement to the lowest bar position in the receiving phase, peak vertical barbell velocity, and net horizontal displacement of the bar were extracted for comparisons of: 1) software programs, 2) smoothing versus filtering and 3) evaluation of intra-rater consistency. These variables

were selected because they are commonly used indicators of weightlifting technique (2, 7, 11, 12, 15, 17, 24). Additional, but less commonly used variables were also analyzed (Tables 2 and 3).

Statistical analyses

Mean and standard deviations (SD) are presented. Mean differences of each variable were compared between the different processing techniques. As only one participant was recorded, no further statistical procedures were appropriate to use.

RESULTS

The time required to digitize and process all repetitions once was approximately 66 minutes or 2 minutes per repetition; both software programs required the same time. The LED-based marker could be automatically tracked for all videos, regardless of camera settings. Visual inspection while the LED-based marker was being auto-tracked found no instances where the software failed to identify the marker. Three of the camera settings provided sufficient image quality to see the LED marker, the entire meter stick, and the lifter (Panels A., B. and E., Figure 2)

Digitizing data in both software programs provided similar results, with mean differences of less than ± 0.02 m and ± 0.01 m for the position data of the snatch and clean, respectively. The mean differences in peak vertical velocity were less than ± 0.07 m·s⁻¹ in the snatch and less than ± 0.01 m·s⁻¹ in the clean between software programs. The smoothed and filtered data had mean differences of less than ± 0.02 m and ± 0.01 m for the position data of the snatch and clean, respectively. The corresponding mean differences in peak vertical velocity were less than ± 0.03 m·s⁻¹ in the snatch and ± 0.04 m·s⁻¹ in the clean. However, the smoothness of the position-time curves differed between different interactions of software and

filtering technique (Figure 3). Specifically, the noise in the data obtained using Tracker was successfully removed with either smoothing or filtering, while only filtering successfully removed the noise in the data obtained using Kinovea. Both software programs were found to provide consistent results. When comparing the first and second digitization, there were mean differences in the position data of less than ± 0.01 m and ± 0.02 m for snatch and clean, respectively. The corresponding mean differences in peak vertical velocity were less than ± 0.04 m·s⁻¹ in the snatch and ± 0.03 m·s⁻¹ in the clean.

Figure 3 about here

The lifter demonstrated the characteristic toward-away-toward bar trajectory in the snatch and clean (Figure 4). When videos were processed using Tracker and smoothed with the five point moving arc, net horizontal bar displacement was -0.15 ± 0.04 m in the snatch and -0.13 ± 0.02 m in the clean. The peak bar displacement relative to the participant's stature was $72.3 \pm 1.9\%$ in the snatch and $58.3 \pm 3.5\%$ in the clean. The difference in vertical position between peak bar height and the height that the bar was received was 0.27 ± 0.04 m and 0.50 ± 0.05 m in the snatch and clean, respectively. Peak bar velocity was 2.29 ± 0.08 m·s⁻¹ in the snatch and 2.04 ± 0.10 m·s⁻¹ in the clean (Figure 5). Peak bar velocity in the back squat was 0.84 ± 0.08 m·s⁻¹. Additional detail on selected key variables are provided in Tables 2 and 3.

Figure 4 & 5 about here

Table 2 & 3 about here

DISCUSSION

This case study demonstrates the ability to quickly analyze two-dimensional bar kinematics during weightlifting exercises using a low-cost LED-based marker, consumer camera and open source software. Further, this investigation has demonstrated that different software and data processing methods yield nearly identical and consistent results. These methods allow researchers and practitioners to obtain bar kinematic data and assess weightlifting technique without the need for either specialized or expensive hardware and software. The specific bar trajectory a lifter displays influences biomechanical parameters, including joint kinematics and the amount of vertical versus horizontal work performed (7, 15). These parameters may affect the muscles trained and the adaptations elicited. Thus, knowledge of the specific bar trajectory displayed is required to interpret and apply findings in research involving weightlifting exercises. The effect of technique on biomechanics is not unique to weightlifting. In running, foot strike pattern affects lower extremity mechanics and ground reaction forces (20). In vertical jumping, net joint moments differ between proximal-to-distal versus simultaneous sequencing strategies (3). In barbell squats, squat depth affects muscle strength adaptations (1). Therefore, research findings cannot be interpreted correctly without considering the technique employed.

In addition to classifying technique, bar trajectory may be used to objectively evaluate a lifter's performance. The participant in this investigation demonstrated the characteristic towards-away-towards bar trajectory that has previously been noted in world and Olympic calibre weightlifters (7, 17). However, magnitudes of vertical and horizontal bar displacements were greater than in world and Olympic calibre weightlifters (7, 11, 13). For example, peak vertical bar displacement in the snatch and clean were 72.3% and 58.3% of the lifter's stature. The best international lifters have a peak vertical bar displacement of 60% and 50% of their stature, respectively, in the snatch and clean (2, 23). This greater vertical bar

displacement resulted in a large drop displacement from peak height to the lowest position in the receiving phase. Based on this evaluation, we can conclude the participant displayed lifting technique that is consistent with that of high calibre lifters. However, by reducing the magnitudes of vertical and horizontal displacement, the participant's performance could be improved, which may allow heavier loads to be lifted.

The kinematic variables used to evaluate the participant's technique in the snatch and clean were consistent between Tracker and Kinovea and across repeated digitizations. The mean differences in the position data obtained using Tracker and Kinovea were less than ± 0.02 m. Given that the LED-based marker has approximately this diameter, accuracy could only be improved by reducing the marker size. Thus, similar accuracy can be expected in either Tracker or Kinovea. Smoothing and filtering the raw data provide similar results for the parameters studied. However, based on visual inspection of horizontal and vertical position data, filtering removed noise more effectively from videos that were processed in Kinovea. Smoothing and filtering were equally effective for videos processed in Tracker.

Various methods have been used to obtain bar trajectories in previous studies. 3D optoelectronic motion analysis is commonly used in biomechanics research; these systems are expensive and, thus, not an option for non-biomechanics researchers and non-research settings (10). Most weightlifting technique research has used film or video, and manual digitization (7, 11, 12). Manually digitizing film and video is time consuming (10). Although auto-tracking features are available in several software programs, the bar end is not easy to auto-track accurately. This is because the bar end does not create a sufficient contrast from the surrounding image to be automatically recognized, even when instrumented with a reflective marker or coloured tape. The addition of an LED-based marker enhanced the ability to automatically track the bar end. As a light emitter, the LED-based marker would focus more

light on the camera's sensor in contrast to the remainder of objects in the field of view, which are light reflectors.

The LED marker and collar assembly has minimal mass and the weight exerted on the bar is small (0.4 N). For comparison, a single linear position transducer has a cable tension of 1.4 N – 8.2 N (4, 5). To determine vertical and horizontal displacement a pair of linear position transducers are required, further increasing the force exerted on the bar (5).

Accelerometers that are marketed for similar purposes are 58 g which would exert 0.6 N. Compared to other instrumentation, an LED-based marker will exert the least force on the bar.

Although the present investigation examined weightlifting, the proposed method could be applied to measure bar kinematics for any barbell exercise, a purpose for which linear position transducers and accelerometers are commonly used (5, 19). An example is provided in the present study of bar velocity during back squat exercise. In addition to exerting less force on the bar, a benefit of this methodology, versus linear position transducers and accelerometers, is that a video record of the lifter is also obtained. A video image of sufficient quality could be used to, either visually or by manually digitizing additional points of interest, evaluate other aspects of the lifter's movement. Further, the video footage can be used to determine movements occurring in other planes, such as bar tilt (frontal plane) or bar rotation (transverse plane) that may invalidate planar assumptions in two-dimensional analysis (8).

In the present study, data were collected on one participant only. However, the ability for software programs to track an LED-based marker is independent of lifting technique, thus, this study presents a proof of concept. In order to auto-track the LED marker, high quality video recordings are paramount. A high quality recording provides a sharp contrast between the LED-marker and its surroundings, while simultaneously providing a good visual record of the lifter (e.g. Figure 2, Panel B.). Further, blurry or pixelated video footage may compromise the accuracy of the auto-tracking, and should be avoided. Video quality is dependent on

sensor resolution, lens and zoom, and ability to adjust exposure settings. The camera and lens used in the present investigation allowed the zoom, shutter speed, aperture and ISO settings to be adjusted. These features allow this camera to record videos with sufficient quality in a large variety of locations and lighting settings. Considering the low cost and high availability of cameras with these features, the methods employed in this study should be available to most researchers, as well as to coaches. Utilizing the methods described would assist coaches in objectively assessing weightlifting technique as exemplified above. Such an assessment can provide detailed information that can help the coaches individualize training to effectively improve their lifters' technique.

In conclusion, using an LED marker provided a sufficient contrast from the surrounding image to obtain two-dimensional bar kinematics using the auto-tracking feature in Tracker and Kinovea. Further, both software packages provided results consistent with each other, and across multiple rounds of data processing. Research involving weightlifting exercises should determine and report the technique used, as study findings may be affected by how the exercises are performed. At minimum, we recommend that participants' bar trajectory should be determined. The current methodology may also be useful to assess bar kinematics in other exercises, having distinct benefits in comparison to commonly used instruments such as linear position transducers and accelerometers.

PRACTICAL APPLICATIONS

This case study proposes a method to examine weightlifting technique using an LED-based marker, consumer camera and open source software. Considering the accessibility and low cost of this method, it is feasible for coaches to use this method to objectively evaluate the technique of athletes performing weightlifting exercises. For example, an individual who does not have the characteristic towards-away-towards trajectory may benefit by improving

their technique to exhibit this trajectory (16, 22). An individual who elevates the bar to an unnecessary height may benefit by focussing on the transition between second pull and squat under phases (6). Moreover, kinematic parameters could be examined periodically, to evaluate training program effectiveness. Ultimately, objective measures, such as bar kinematics, of how an exercise is performed provides information that may be used to enhance training efficacy.

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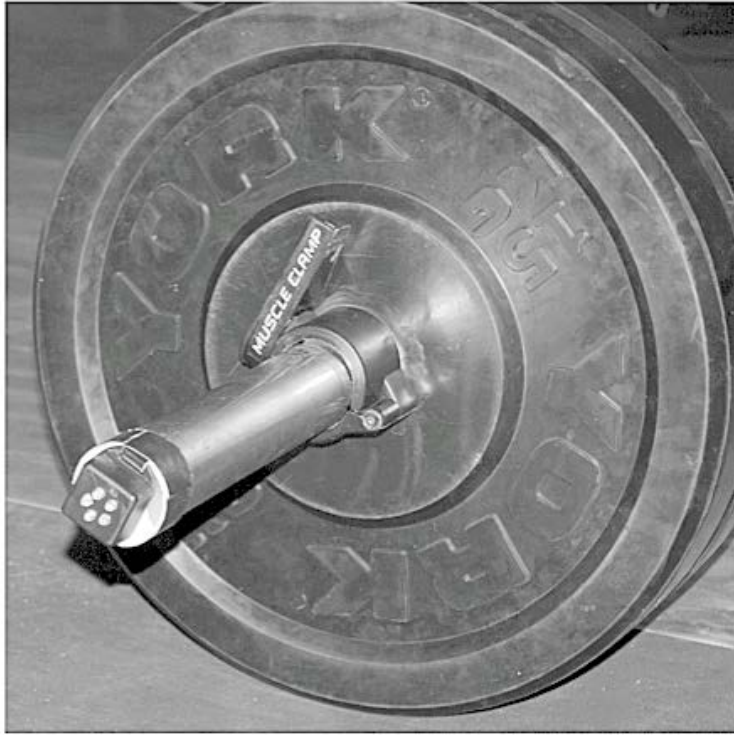


Figure 1. The LED marker and collar assembly placed on the right bar end.

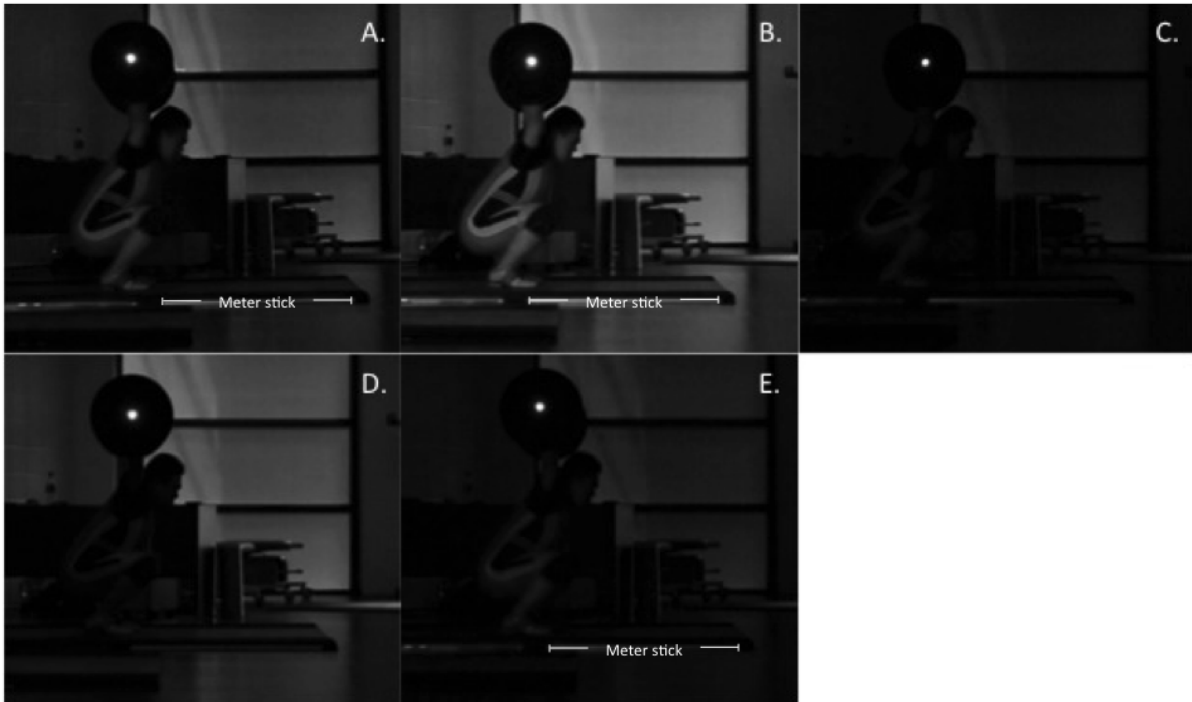


Figure 2. Individual frames from set 1 (A.), 2 (B.), 3 (C.), 4 (D.) and 5 (E.) of the snatch, captured with various camera settings (Table 1). For videos with sufficient quality to view, the reference length meter stick is highlighted (A., B. and E.).

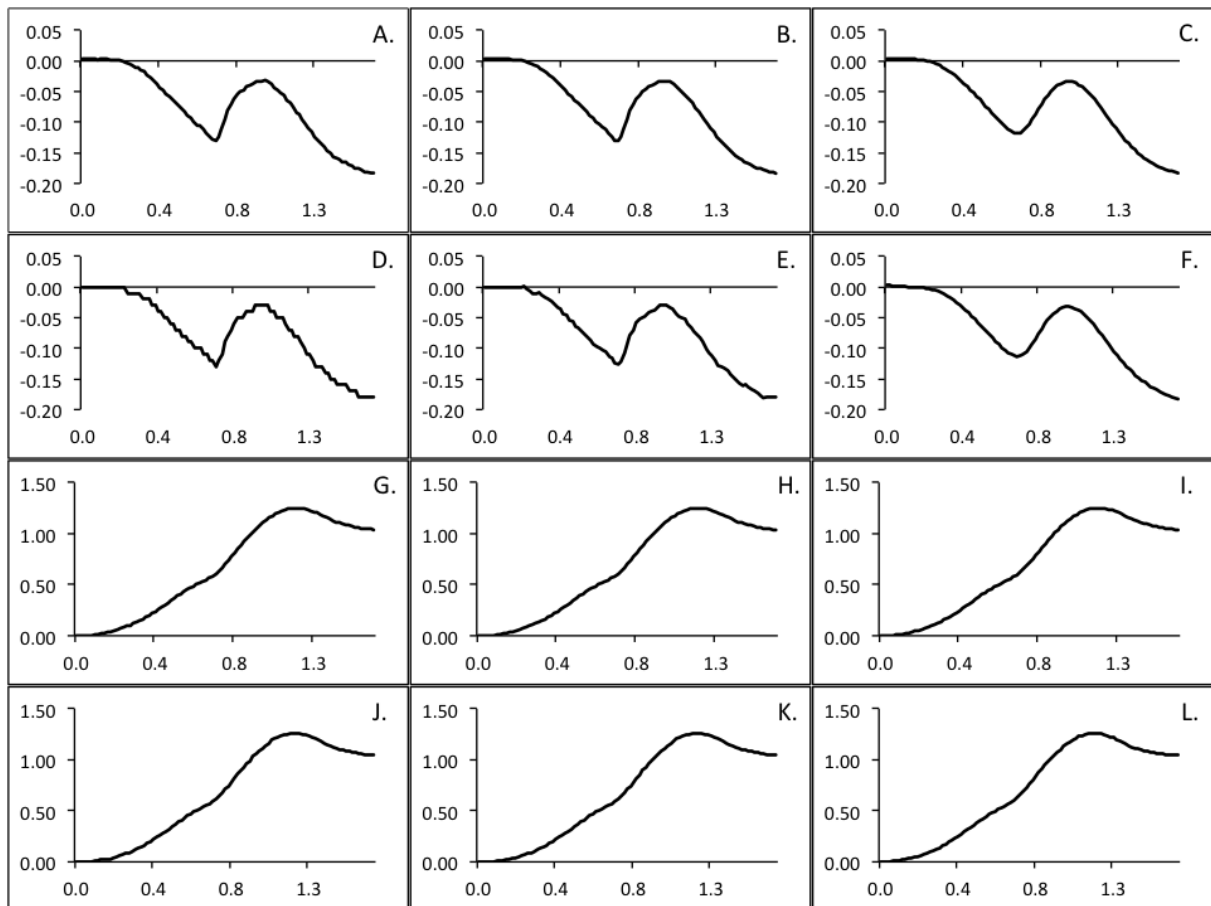


Figure 3. Raw (A., D., G. and J.), smoothed (B., E., H. and K.) and filtered (C., F., I. and L.) horizontal (A. through F.) and vertical (G. through L.) position coordinates from a representative snatch lift. Data obtained from Tracker are shown in panels A. through C. and G. through I. Data obtained in Kinovea are shown in panels D. through F. and J. through L. The horizontal axes indicate time (s) and the vertical axes indicate displacement (m).

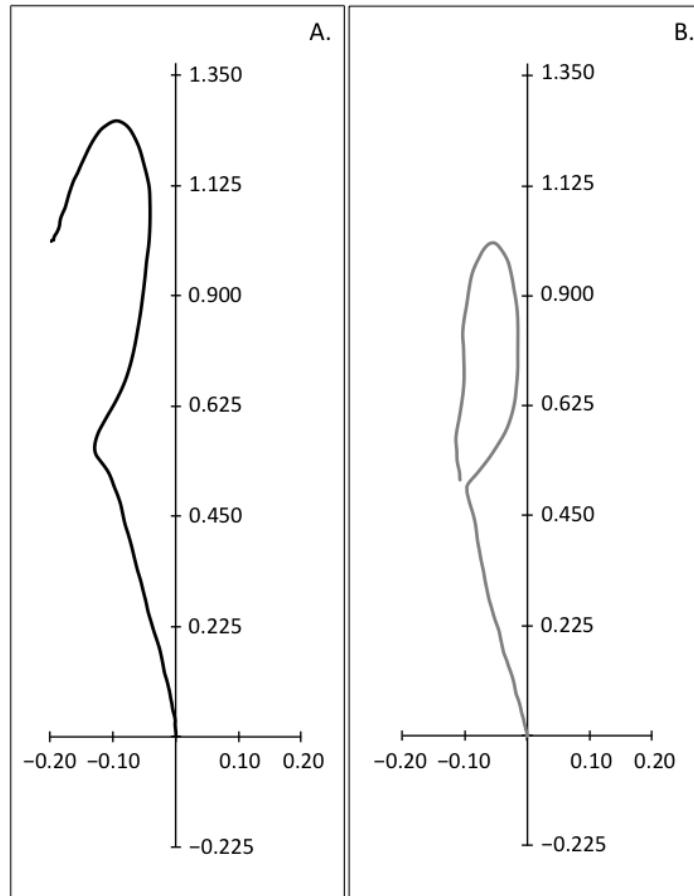


Figure 4. A representative bar trajectory of the participant's snatch (A.) and clean (B.). Positive values indicate superior and anterior with respect to the bar's position at lift-off.

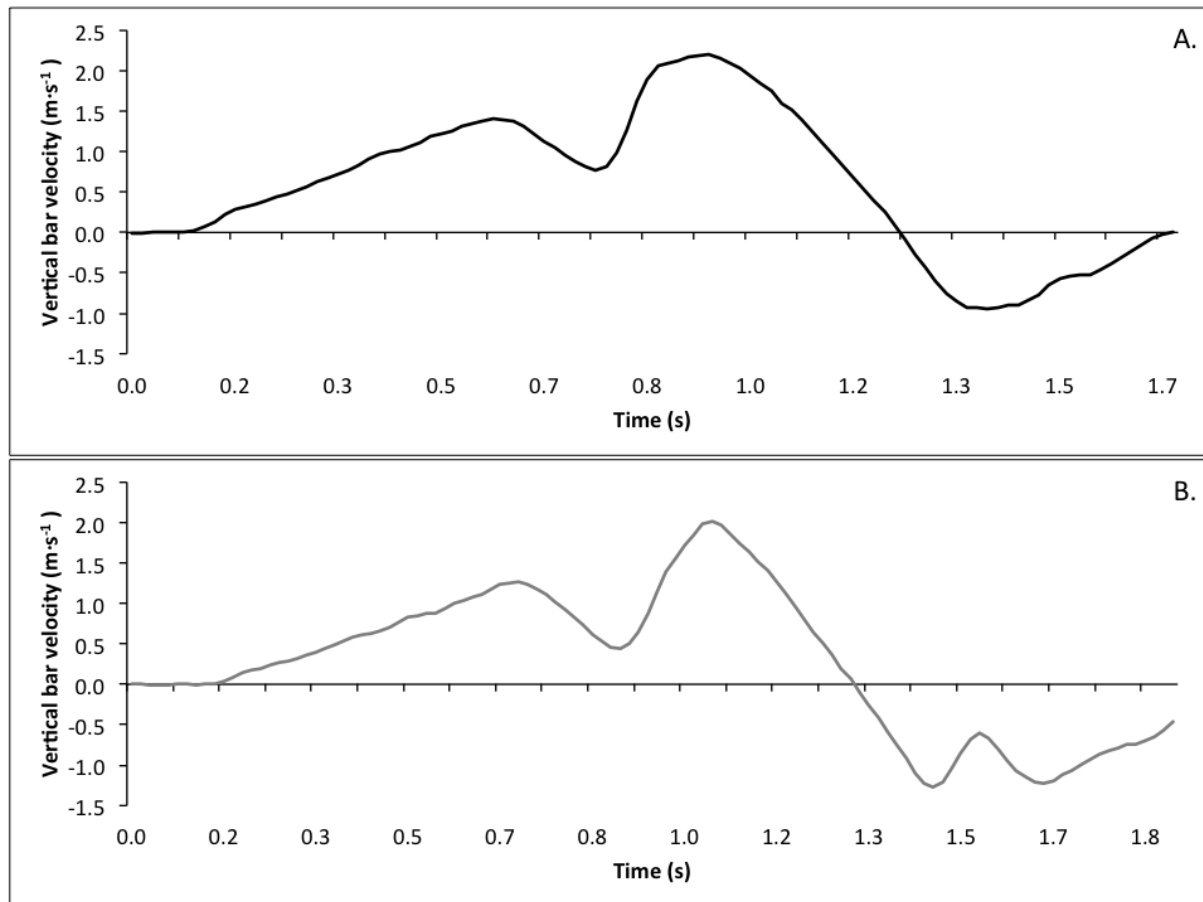


Figure 5. The vertical bar velocity of a representative snatch (A.) and clean (B.).

Table 1. Barbell load, repetitions, shutter speed and ISO setting used for the individual sets of the snatches and cleans.

<i>Exercise</i>	<i>Set</i>	<i>Barbell Load</i>	<i>Repetitions</i>	<i>Shutter Speed</i>	<i>ISO</i>
Snatch	1	50 kg	3	1/500	800
Snatch	2	50 kg	3	1/250	800
Snatch	3	50 kg	3	1/1250	800
Snatch	4	50 kg	3	1/100	100
Snatch	5	70 kg	2	1/500	400
Snatch	6	70 kg	2	1/500	800
Snatch	7	90 kg	1	1/500	400
Snatch	8	100 kg	1	1/500	400
Snatch	9	100 kg	1	1/500	400
Snatch	10	100 kg	1	1/500	400
Clean	1	50 kg	2	1/500	400
Clean	2	50 kg	2	1/500	400
Clean	3	90 kg	1	1/500	400
Clean	4	110 kg	1	1/500	400
Clean	5	120 kg	1	1/500	400
Clean	6	120 kg	1	1/500	400
Clean	7	120 kg	1	1/500	400
Back Squat	1	120 kg	2	1/500	400
Back Squat	2	140 kg	1	1/500	400
Back squat	3	140 kg	1	1/500	400

Table 2. Comparisons of the two software packages, smoothing and filtering, and intra-rater consistency for the snatch lifts. Mean and standard deviation is presented.

		Snatch					
		<i>T1 5MA</i>	<i>T1 FD</i>	<i>T2 5MA</i>	<i>K1 5MA</i>	<i>K1 FD</i>	<i>K2 FD</i>
$s_{Y_{peak}}$	(m)	1.29 ± 0.03	1.29 ± 0.03	1.28 ± 0.03	1.31 ± 0.04	1.31 ± 0.04	1.30 ± 0.04
$s_{Y_{drop}}$	(m)	0.27 ± 0.04	0.27 ± 0.04	0.27 ± 0.04	0.28 ± 0.04	0.28 ± 0.04	0.27 ± 0.04
$v_{Y_{peak}}$	(m·s ⁻¹)	2.29 ± 0.08	2.29 ± 0.08	2.28 ± 0.08	2.36 ± 0.10	2.34 ± 0.10	2.31 ± 0.09
s_{X_1}	(m)	-0.12 ± 0.01	-0.11 ± 0.01	-0.12 ± 0.01	-0.12 ± 0.02	-0.11 ± 0.02	-0.11 ± 0.01
s_{X_2}	(m)	0.13 ± 0.03	0.12 ± 0.03	0.13 ± 0.03	0.14 ± 0.03	0.12 ± 0.03	0.12 ± 0.03
$s_{X_{loop}}$	(m)	-0.16 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02
$s_{X_{net}}$	(m)	-0.15 ± 0.04	-0.15 ± 0.04	-0.15 ± 0.04	-0.15 ± 0.04	-0.15 ± 0.04	-0.15 ± 0.04

$s_{Y_{peak}}$ = peak vertical bar displacement, $s_{Y_{drop}}$ = drop in bar height from $s_{Y_{peak}}$ to the bottom position of the receiving phase, $v_{Y_{peak}}$ = peak vertical bar velocity, s_{X_1} = horizontal bar displacement during the first pull, s_{X_2} = horizontal bar displacement during the transition phase and second pull, $s_{X_{loop}}$ = horizontal bar displacement during the turnover and receiving phase, $s_{X_{net}}$ = net horizontal bar displacement, T1 = digitization 1, Tracker, T2 = digitization 2, Tracker, K1 = digitization 1, Kinovea, K2 = digitization 2, Kinovea, 5MA = Five-point moving arc, FD = Filtered data.

Table 3. Comparisons of the two software packages, smoothing and filtering, and intra-rater consistency for the clean lifts. Mean and standard deviation is presented.

		Clean					
		<i>T1 5MA</i>	<i>T1 FD</i>	<i>T2 5MA</i>	<i>K1 5MA</i>	<i>K1 FD</i>	<i>K2 FD</i>
$s_{Y_{peak}}$	(m)	1.04 ± 0.06	1.04 ± 0.06	1.02 ± 0.04	1.03 ± 0.04	1.03 ± 0.04	1.04 ± 0.05
$s_{Y_{drop}}$	(m)	0.50 ± 0.05	0.50 ± 0.05	0.50 ± 0.04	0.50 ± 0.04	0.50 ± 0.04	0.51 ± 0.04
$v_{Y_{peak}}$	(m·s ⁻¹)	2.04 ± 0.10	2.02 ± 0.12	2.01 ± 0.06	2.05 ± 0.08	2.01 ± 0.07	2.03 ± 0.09
s_{X_1}	(m)	-0.10 ± 0.01	-0.09 ± 0.01	-0.10 ± 0.01	-0.10 ± 0.01	-0.09 ± 0.02	-0.09 ± 0.01
s_{X_2}	(m)	0.08 ± 0.01	0.07 ± 0.01	0.08 ± 0.01	0.08 ± 0.01	0.08 ± 0.02	0.07 ± 0.01
$s_{X_{loop}}$	(m)	-0.11 ± 0.01	-0.11 ± 0.01	-0.11 ± 0.01	-0.11 ± 0.01	-0.11 ± 0.01	-0.11 ± 0.01
$s_{X_{net}}$	(m)	-0.13 ± 0.02	-0.13 ± 0.01	-0.13 ± 0.02	-0.13 ± 0.02	-0.13 ± 0.01	-0.13 ± 0.02

$s_{Y_{peak}}$ = peak vertical bar displacement, $s_{Y_{drop}}$ = drop in bar height from $s_{Y_{peak}}$ to the bottom position of the receiving phase, $v_{Y_{peak}}$ = peak vertical bar velocity, s_{X_1} = horizontal bar displacement during the first pull, s_{X_2} = horizontal bar displacement during the transition phase and second pull, $s_{X_{loop}}$ = horizontal bar displacement during the turnover and receiving phase, $s_{X_{net}}$ = net horizontal bar displacement, T1 = digitization 1, Tracker, T2 = digitization 2, Tracker, K1 = digitization 1, Kinovea, K2 = digitization 2, Kinovea, 5MA = Five-point moving arc, FD = Filtered data.