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Article

Biomechanical differences in maximum snatch weight between elite and sub-elite weightlifters: A one-dimensional statistical parameter mapping study

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Abstract: Background: Current research primarily relies on discrete data collected at specific time points to analyze the weightlifting process, often overlooking the impact of continuous temporal changes on athletic performance. **Purpose:** This study aimed to quantitatively analyze the one-dimensional kinematic patterns of maximum snatch weight actions in elite and sub-elite weightlifters using statistical parameter mapping (SPM). It explores kinematic differences in snatch actions between elite and sub-elite weightlifters, which assists in summarizing the technical characteristics of elite athletes. **Methods:** Two cameras recorded three successful maximum snatch attempts of 10 elite and 10 sub-elite weightlifters at the World Weightlifting Championships and Chinese Olympic selection competitions. Simi Motion 10.2 was used for kinematic analysis. SPM was employed for comparative analysis of snatch kinematics among different levels of weightlifters, and independent sample t-tests were used for phase duration proportions. **Results:** Elite weightlifters showed significant advantages in multiple movement phases: smaller knee joint angles in M1 phase ($p < 0.001$, 35.82%–78.45%) and M3 phases (p = 0.047, 17.47%–24.74%; $p = 0.036$, 30.92%–49.38%; $p = 0.040$, 50.93%–65.85%); lower vertical body center of gravity (COG) height in M1 phase ($p = 0.019$, 0.00%–51.08%), M3 phase ($p = 0.046$, 48.27%–100.00%), and M5 phase ($p = 0.045$, 38.49%–59.54%); closer displacement between barbell COG and body COG in M1 phase ($p = 0.006$, 0%–38.18%; $p = 0.048$, 43.91%–48.94%) and M2 phase ($p = 0.026$, 0%–100%); greater barbell acceleration in M5 phase ($p < 0.001$, 0%–94.61%); and slower barbell descent speed in M6 phase ($p = 0.001$, 0%–30.58%; $p = 0.046$, 44.57%–51.37%; $p = 0.048$, 67.16%–72.41%). Moreover, elite weightlifters exhibited significantly higher phase duration proportions in M1 phase ($p = 0.034$, $d = 1.03$) than sub-elite weightlifters. **Conclusion:** Elite weightlifters demonstrated longer distance and time exerting work on the barbell in M1 phase, less energy consumption in barbell ascent in M2 phase, and greater upward power gain for the barbell in M1 and M3 phases. They showed faster squat-to-barbell catching speed in M4 phase and excellent braking and precise squat-to-barbell catching capabilities in M5 and M6 phases.

Keywords: snatch technique; statistical parametric mapping; weightlifting; kinematics; biomechanics

1. Introduction

Olympic weightlifting includes the snatch and clean and jerk. Athletes are categorized into different weight classes, with each allowed three attempts, and once successful, lifters must increase the weight by at least 1 kg [1]. Athletes are ranked according to the highest total weight lifted in the snatch and clean and jerk. Among these actions, the snatch is the most technically demanding movement [2], which is characterized by its speed [3]. The barbell is lifted from the ground to overhead in a continuous motion in less than 1.5 s [4], which requires athletes to possess excellent technique, strength, flexibility, and body speed [2,5].

In snatch technique research, scholars have used two-dimensional [6,7] or three-dimensional (3D) kinematic analysis techniques [8,9] to study biomechanical parameters during the snatch process. Previous snatch studies have focused on case analyses of Olympic champions [10], as well as comparative analyses among weightlifting categories[9], genders[11], or age groups[12]. However, limited research is available on the kinematic differences in snatch movements among athletes of different ability levels. Elite athletes' technique represents the best performances and can be considered excellent technical models or references to be achieved [13]. Contrasting the snatch kinematics between elite and sub-elite athletes can summarize the technical characteristics of elite athletes, which provides valuable information for sub-elite athletes and coaches to integrate into training, improve performance, and compete.

Currently, kinematic studies on weightlifting have not utilized standardized statistics for differentiation and research. In traditional snatch research, one-dimensional (1D) kinematics and barbell trajectories are typically analyzed using discrete data from different stages (0D) to conduct quantitative statistical analysis and qualitative reporting results [8,14], but 1D trajectory magnitude and numerical trends are qualitatively explored [15]. Method one quantitatively analyzed 0D data for each stage but ignored the continuity of the movement, which resulted in failure to obtain statistical differences within each stage; method two, while focusing on the coherence of kinematics in time series, cannot be used to scientifically analyze differences. Previous snatch studies inevitably encountered statistical type I errors. Statistical parameter mapping (SPM) technology adds a time component to quantitative analysis and focuses on time series parameters in topological analysis based on random field theory [16]. SPM has been widely applied in biomechanics research, particularly in studies examining behavioral differences within time-series data. Notable examples of its application include investigations of volleyball players' landing after spiking[17], single-leg landing tests conducted in laboratory settings[18], and gait analysis[19]. SPM technology is more suitable for forming probabilistic conclusions regarding 1D kinematics and effectively reducing the possibility of type I errors. SPM is based on random field theory for topological analysis, which calculates the statistical significance of data clusters exceeding thresholds. Specifically, while 0D analyzes specific values at specific moments, SPM conducts holistic analysis of parameter variations over time, which provides quantitative analysis of 1D data to identify areas of statistical differences in time series. In some cases, 0D analysis may not reveal statistical differences, whereas 1D analysis may detect them.

Therefore, this study aims to explore the 1D kinematic differences in snatch movements between elite and sub-elite weightlifters and summarize the technical characteristics of elite weightlifters. Our hypotheses are twofold. 1) Elite weightlifters exhibit lower body center at the start of the snatch than sub-elite weightlifters. 2) No significant difference exists in the maximum height of the barbell.

2. Methods

2.1. Participants

This study focuses on the snatch technique of elite weightlifters (n = 10) and sub-elite weightlifters (n = 10) in the 73 kg weight category. Athletes lifted their maximum successful weights during competition. Elite weightlifters are defined as 1) athletes ranked in the top three in national, world, or Olympic weightlifting competitions in the 73 kg category, and 2) members of the Chinese national team. Sub-elite weightlifters are defined as athletes ranked second to seventh in the Chinese Weightlifting Championships (Level 2 weightlifting events), who are considered sub-elite in this context.

2.2. Data collection and processing

During competitions, two SONY Z90 cameras (Sony Corporation, Japan) were used with a filming frequency of 50 frames per second. These cameras were positioned on the left and right sides in front of the lifting platform, with an approximately 90° angle between their main axes passing through the center axis of the platform. The cameras' positions and filming conditions were kept consistent after calibration using the Peak framework to calibrate the 3D space at the competition venue[13,20]. Accordingly, the coordinate system with the X-axis for front-back, Y-axis for left-right, and Z-axis for vertical directions was set (**Figure 1**)[13].

SIMI Motion 10.2 (SIMI Reality Motion Systems GmbH, Germany), which is a 3D motion analysis system, was used to process the videos at a sampling frequency of 50 Hz. The raw data underwent smoothing with a low-pass filter set at a cutoff frequency of 6 Hz [21]. The direct linear transform algorithm was employed to calculate spatial coordinates [22]. Seventeen key anatomical landmarks were identified for the digital analysis of lifting techniques, including the head, the left and right shoulder joint centers, left and right elbow joint centers, left and right wrist joint centers, left and right hip joint centers, left and right knee joint centers, left and right ankle joint centers, left and right toe tips, as well as the left and right endpoints of the barbell. Based on the Hanavan mathematical model of the human body, the center of gravity (COG) of the athlete was calculated. To ensure accuracy, the barbell's position was digitized manually five times at random, and each of these attempts was analyzed five times. Intra-class correlation coefficients (ICCs) were used to assess the retest reliability of digitized barbell kinematic parameters [23]. Coefficients less than 0.50 indicate poor reliability, those from 0.50 to 0.75 mean moderate reliability, those from 0.75 to 0.90 imply good reliability, and those greater than 0.90 suggest excellent reliability [24].

The variables analyzed in this study are as follows: 1) time of duration for each phase of the snatch action; and 2) 1D variables including sagittal plane kinematics of lower limb joints, COG kinematics, barbell kinematics, and displacement between COG of barbell and COG of body (DCC) [13,15].

MATLAB R2019a (The MathWorks, Natick, MA, United States) was used for linear interpolation to standardize lower limb and barbell kinematic data to 101 data points.

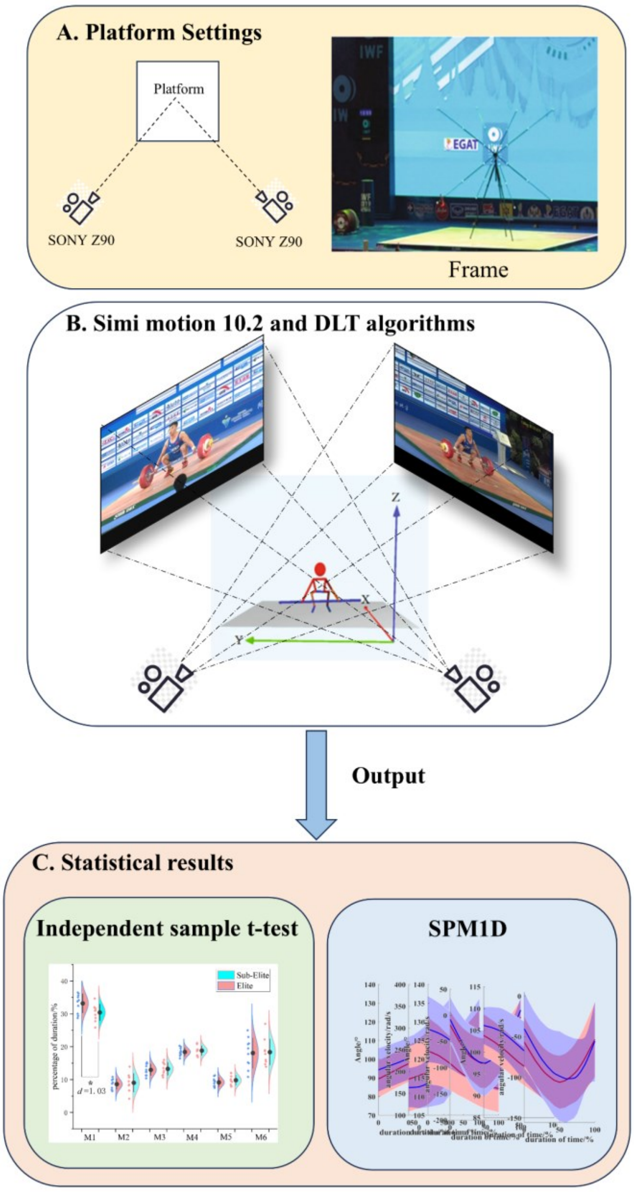


Figure 1. Experimental setup.

2.3. Phase division

Segmenting a rapid continuous action into phases is an efficient method in the field of motion analysis. Previous studies have segmented the snatch action into five phases based on changes in knee angles and barbell heights: the first pull, the transition phase, the second pull, the turnover under the barbell, and the catch phase [5,8,9]. The first five phases of the snatch are considered the most critical [12]. In this study, based on the method by Liu et al., the snatch process (from starting position to squatting position) was divided into six stages[13] (**Table1**, **Figure 2**), which were determined based on changes in knee angle direction, barbell vertical velocity, and barbell vertical height.

Table 1. The first 6 phases of the snatch technique.

The phases of the snatch	Commentary
The first phase(M1)	from start position to the instant of first maximum knee extension angle;
The second phase(M2)	the instant of knee angle from maximum to minimum;
The third phase(M3)	from the end of M2 to the maximum vertical rising velocity of barbell;
The fourth phase(M4)	from the end of M3 to the maximum vertical height of barbell;
The fifth phase(M5)	from the end of M4 to the maximum vertical falling velocity of barbell;
The sixth phase(M6)	from the end of M5 to squat position.

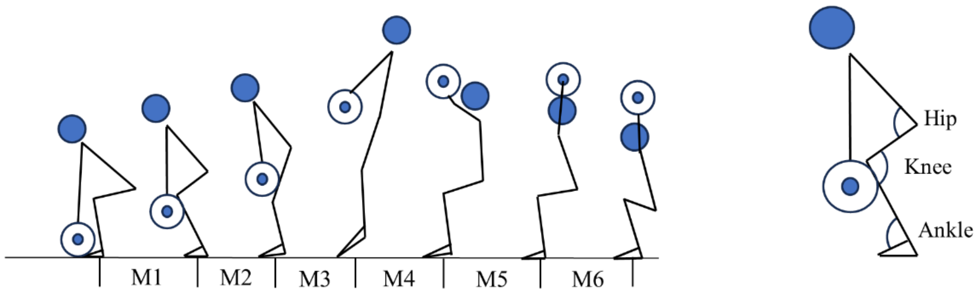


Figure 2. Each stage of snatch movement is divided into the moment characteristic screen.

2.4. Statistical analyses

MATLAB R2019a (The MathWorks, Natick, MA, United States) was used for statistical analysis of kinematic data. The statistical analysis process for each key point included 1) Kolmogorov—Smirnov test for normality and 2) independent sample t-test for normally distributed data and Mann—Whitney U test for non-normally distributed data. Variables were presented as mean ± standard deviation (M±SD). The statistical significance level was set at $\alpha < 0.05$. Cohen's d was used to evaluate effect sizes, which were defined as small (0–0.19), medium (0.20–0.49), large (0.50–0.79), and very large (≥ 0.80) [25].

For continuous variables of lower limb kinematics, SPM analysis was conducted using the open-source package spm1d (http://spm1d.org) in MATLAB R2019a. The analysis process included 1) normality test for each continuous variable and 2) SPM for normally distributed data and SnPM for non-normally distributed data.

3. Results

The results of this study demonstrate good reliability of ICCs for barbell kinematic parameters (0.981 ± 0.004, minimum: 0.974, maximum: 0.990). No statistically significant difference in height was found between elite and sub-elite weightlifters ($p = 0.584$, $d = 0.25$). However, elite weightlifters lifted significantly heavier weights than sub-elite weightlifters ($p = 0.001$, $d = 1.74$) (**Table 2**). Elite weightlifters also spent a significantly higher proportion of time in Phase M1 than sub-elite weightlifters ($p = 0.034$, $d = 1.03$) (**Figure3**).

Table 2. Athlete basic information.

	Elite (*n* = 10)	Sub-Elite (*n* = 10)	*p*-value	Cohen's d
Best result /kg	148.80 ± 6.71	136.80 ± 7.05	0.001	1.74
Height /cm	168.90 ± 3.00	168.00 ± 4.14	0.584	0.25

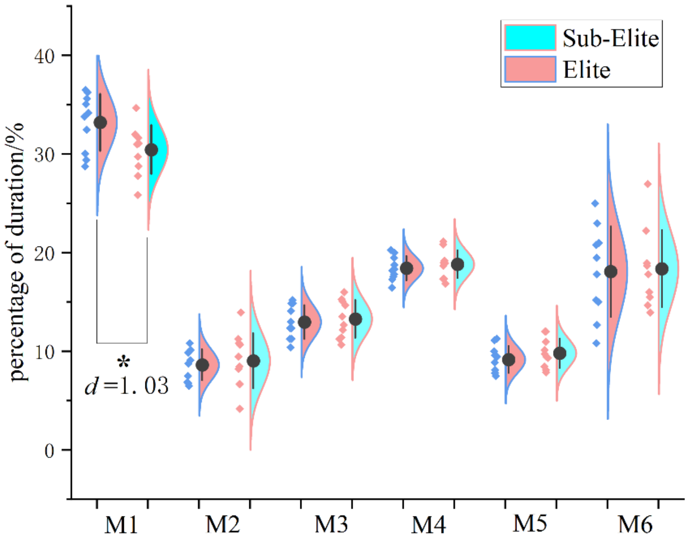
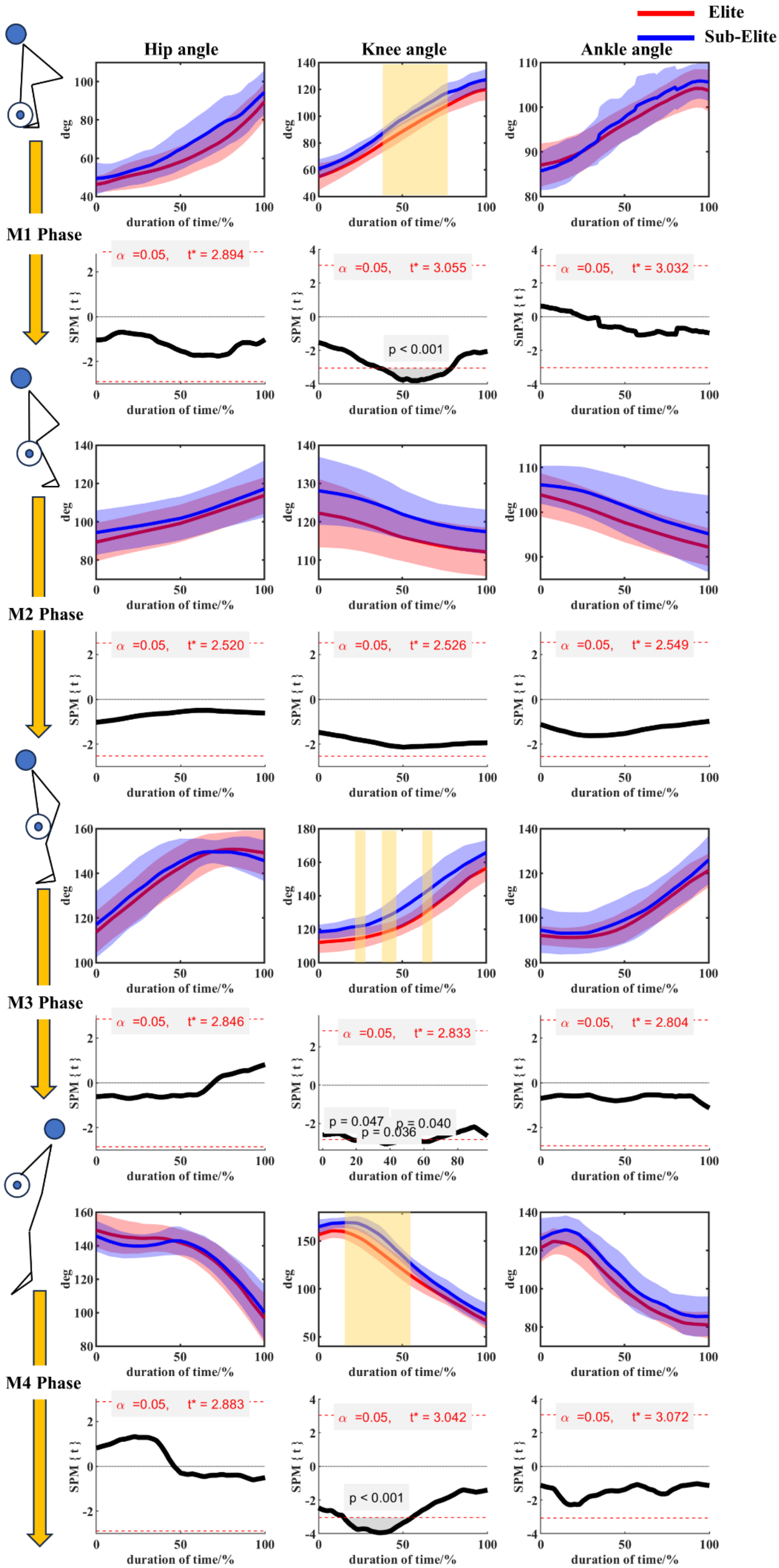


Figure 3. The proportion of time spent in each phase.

In lower limb kinematics, our study found that elite weightlifters had smaller knee joint angles in Phases M1 ($p < 0.001$, 35.82%–78.45%), M3 ($p = 0.047$, 17.47%–24.74%; $p = 0.036$, 30.92%–49.38%; $p = 0.040$, 50.93%–65.85%), and M4 ($p < 0.001$, 14.96%–55.25%). No significant differences were observed in other joint angles (**Figure 4**).

In human–barbell kinematics, elite weightlifters exhibited significantly lower vertical COG heights in Phases M1 ($p = 0.019$, 0.00%–51.08%), M3 ($p = 0.046$, 48.27%–100.00%), and M5 ($p = 0.045$, 38.49%–59.54%) than sub-elite weightlifters. Elite weightlifters' displacement between COG of barbell and COG of body (DCC) was closer to zero in the vertical direction in Phases M1 ($p = 0.006$, 0%–38.18%; $p = 0.048$, 43.91%–48.94%) and M2 ($p = 0.026$, 0%–100%) than that of sub-elite weightlifters. Elite weightlifters also exhibited greater barbell acceleration in Phase M5 ($p < 0.001$, 0%–94.61%) and slower barbell descent speeds in Phase M6 ($p = 0.001$, 0%–30.58%; $p = 0.046$, 44.57%–51.37%; $p = 0.048$, 67.16%–72.41%) (**Figures 5** and **6**).


Elite
Sub-Elite
Hip angle
Knee angle
Ankle angle
M1 Phase
M2 Phase
M3 Phase
M4 Phase
deg
duration of time/%
SPM { t }
α =0.05, t* = 2.894
α =0.05, t* = 3.055
α =0.05, t* = 3.032
p < 0.001
α =0.05, t* = 2.520
α =0.05, t* = 2.526
α =0.05, t* = 2.549
α =0.05, t* = 2.846
α =0.05, t* = 2.833
α =0.05, t* = 2.804
p = 0.047
p = 0.036
p = 0.040
α =0.05, t* = 2.883
α =0.05, t* = 3.042
α =0.05, t* = 3.072
p < 0.001

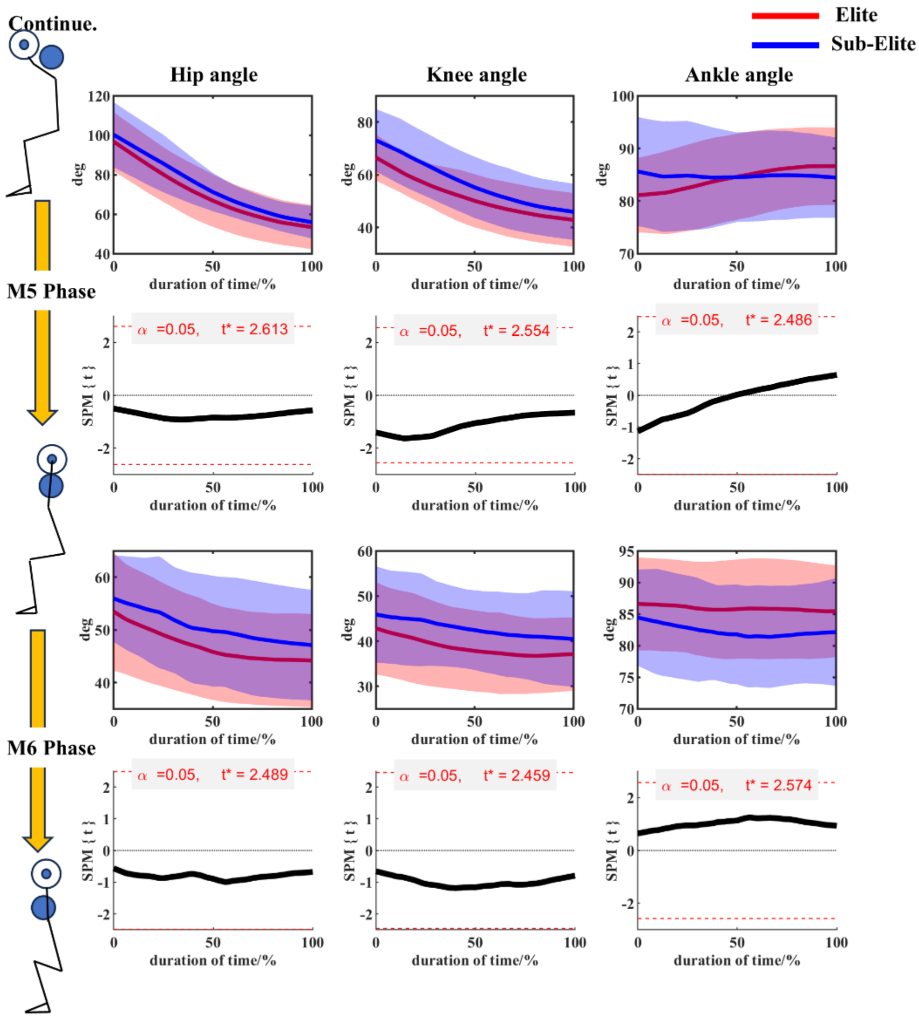
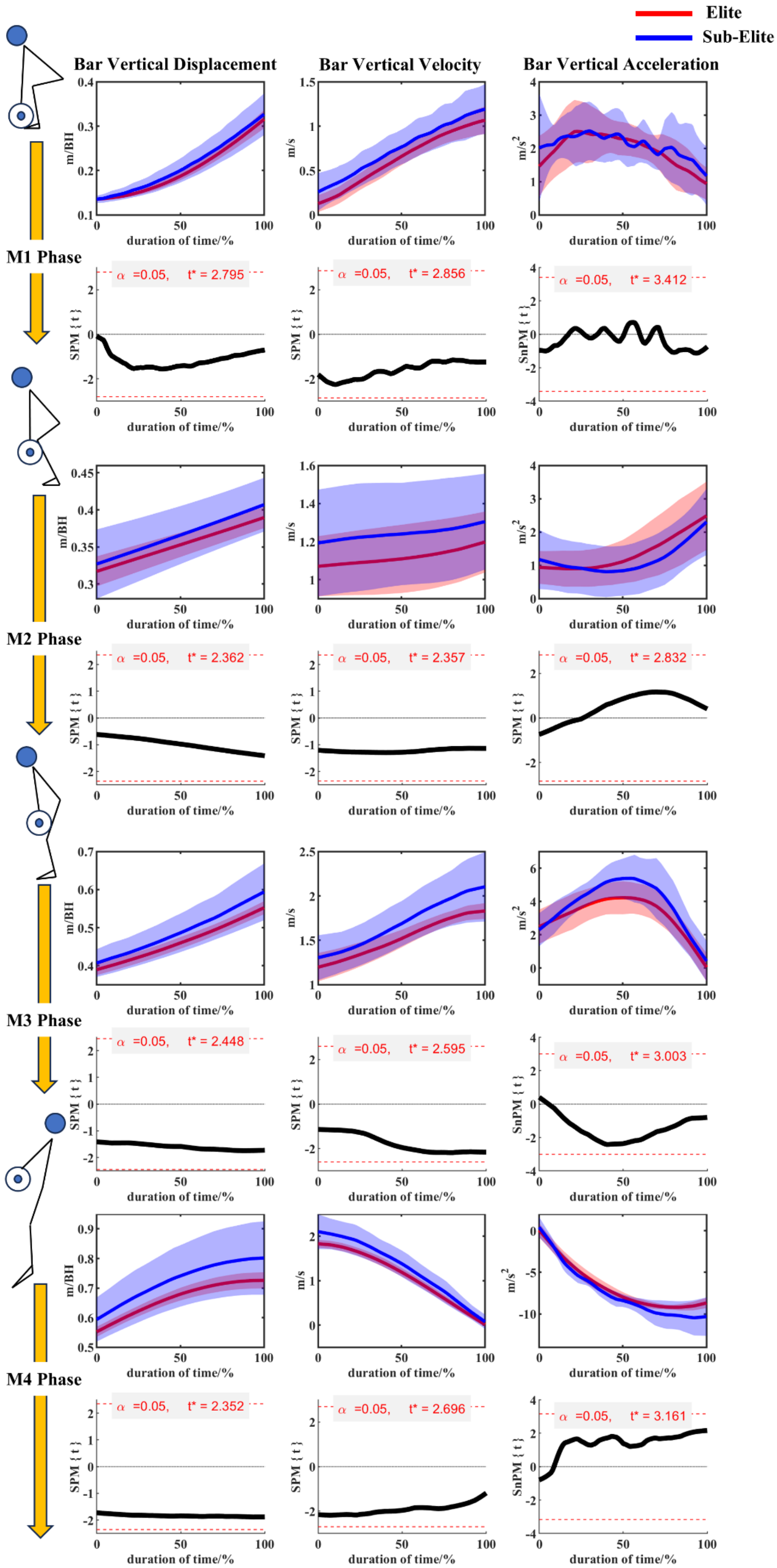


Figure 4. Time series curves of lower limb joint angles.



Elite
Sub-Elite
Bar Vertical Displacement
Bar Vertical Velocity
Bar Vertical Acceleration
M1 Phase
M2 Phase
M3 Phase
M4 Phase
m/BH
m/s
m/s²
SPM {t}
SnPM {t}
duration of time/%
α =0.05, t* = 2.795
α =0.05, t* = 2.856
α =0.05, t* = 3.412
α =0.05, t* = 2.362
α =0.05, t* = 2.357
α =0.05, t* = 2.832
α =0.05, t* = 2.448
α =0.05, t* = 2.595
α =0.05, t* = 3.003
α =0.05, t* = 2.352
α =0.05, t* = 2.696
α =0.05, t* = 3.161

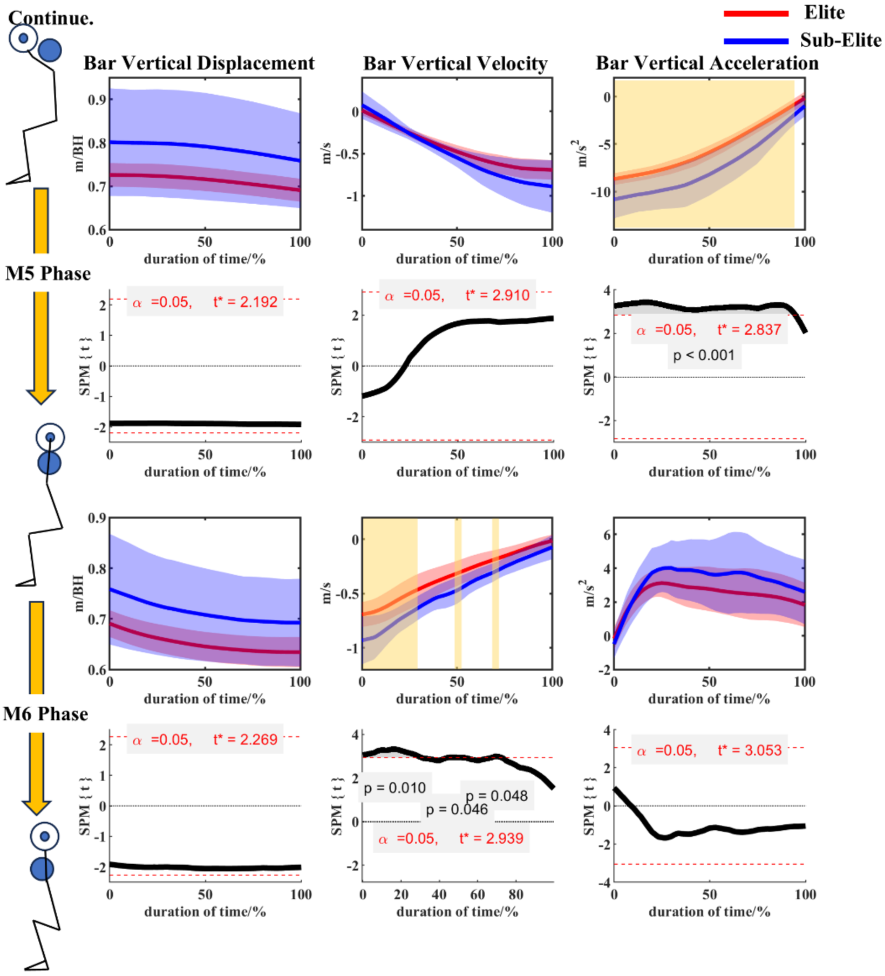
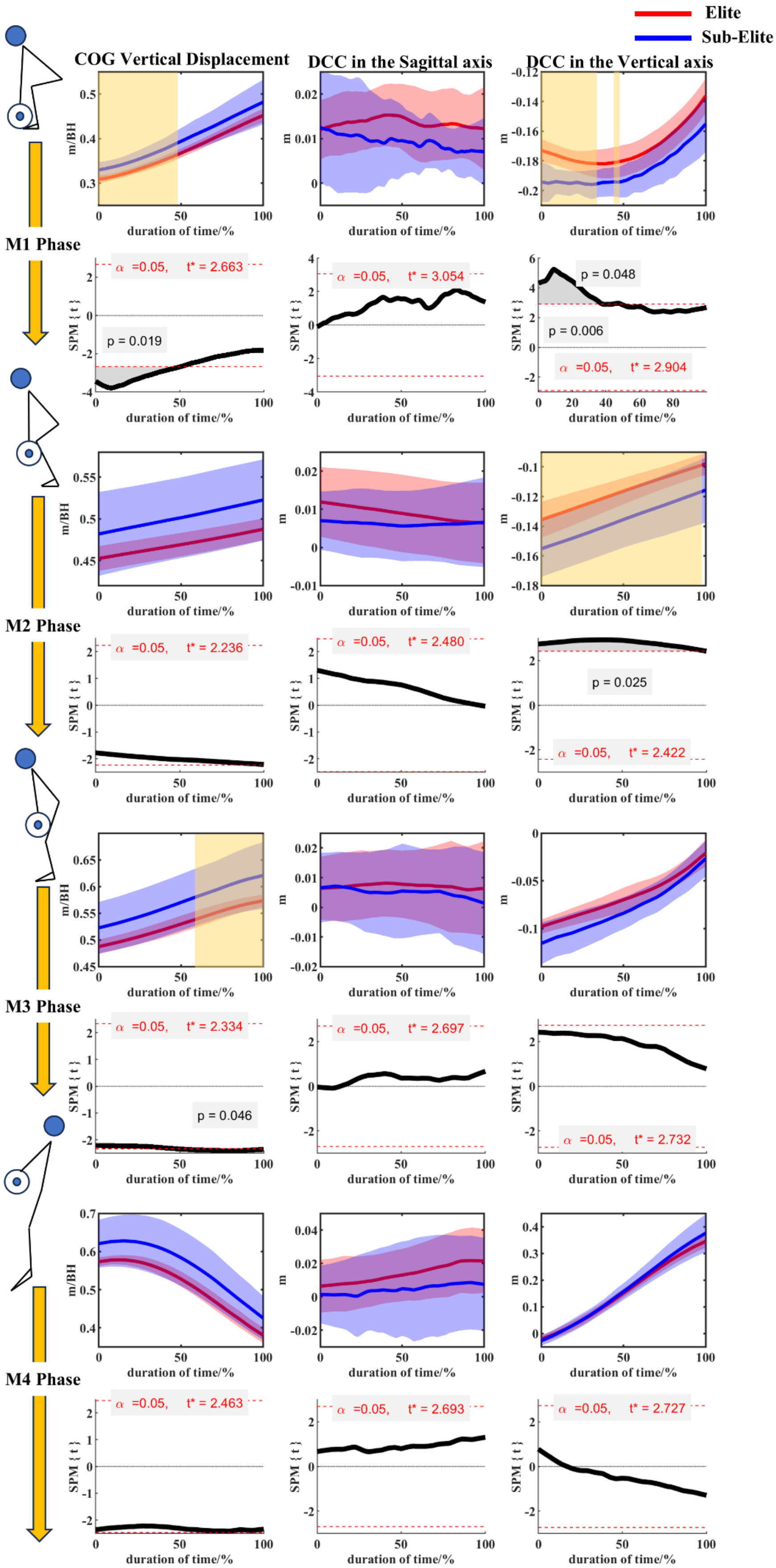


Figure 5. Barbell kinematics time series curve.


Elite
Sub-Elite
COG Vertical Displacement
DCC in the Sagittal axis
DCC in the Vertical axis
M1 Phase
M2 Phase
M3 Phase
M4 Phase
m/BH
m
SPM {t}
duration of time/%
α =0.05, t* = 2.663
p = 0.019
α =0.05, t* = 3.054
p = 0.048
p = 0.006
α =0.05, t* = 2.904
α =0.05, t* = 2.236
α =0.05, t* = 2.480
p = 0.025
α =0.05, t* = 2.422
α =0.05, t* = 2.334
p = 0.046
α =0.05, t* = 2.697
α =0.05, t* = 2.732
α =0.05, t* = 2.463
α =0.05, t* = 2.693
α =0.05, t* = 2.727

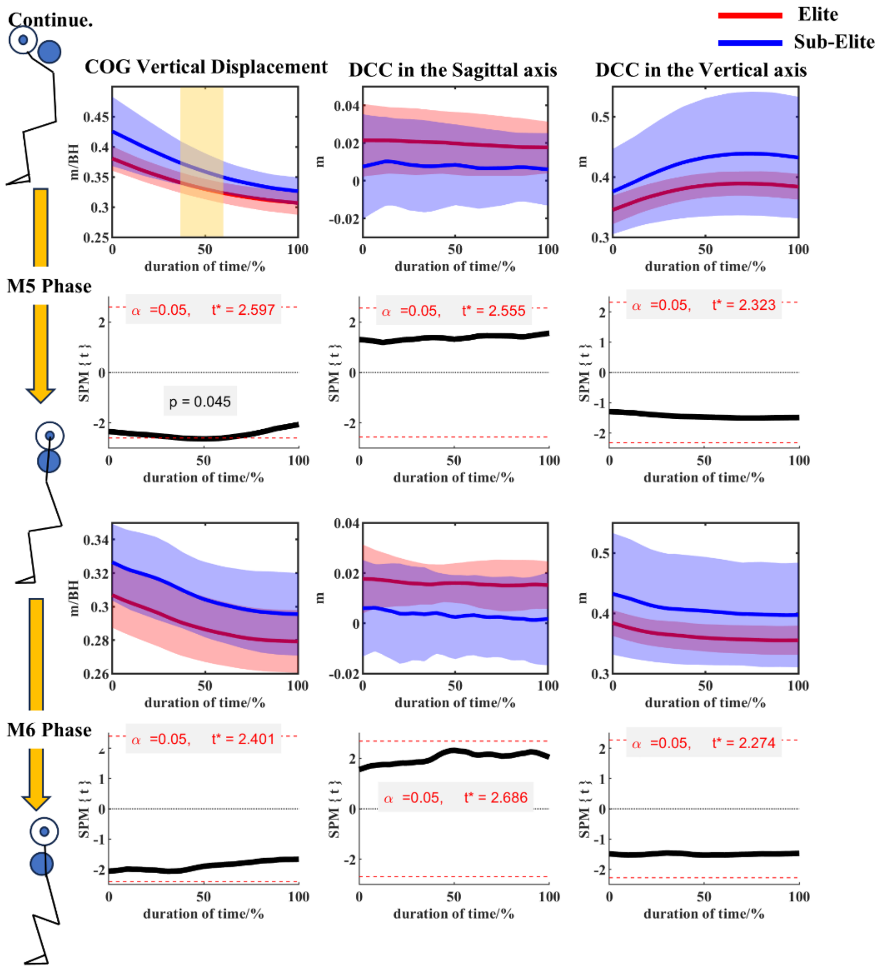


Figure 6. Kinematic time series curves of COG and DCC.

4. Discussion

This study represents the first application of SPM in weightlifting research. It specifically explores 1D kinematic differences in the snatch movement between elite and sub-elite male weightlifters in the 73 kg category. Our findings support our two research hypotheses: elite weightlifters exhibit lower body COG at the beginning of the snatch movement in Phase M1, and no significant differences are found in the maximum barbell height reached by the end of Phase M4. Our study indicates that elite weightlifters spent a longer proportion of time in Phase M1 than sub-elite weightlifters. The former had smaller knee joint angles in Phases M1, M3, and M4 than the latter. In terms of vertical human COG height, those of elite weightlifters were significantly lower than those of sub-elite weightlifters in Phases M1, M3, and M5. Furthermore, the DCC positions of elite weightlifters were closer to zero in the vertical direction in Phases M1 and M2, and they exhibited greater barbell acceleration in Phase M5. Moreover, elite weightlifters showed slower barbell descent speeds in Phase M6.

Phases M1–M4 represent the phases during which the barbell moves upward, which indicates a positive work. Exceptional weightlifters can effectively utilize muscle strength to promote barbell movement and make rational assessments of barbell movement states [26]. Our study found that elite weightlifters exhibited significantly lower COG height (0.00%–51.08% in M1) and DCC vertical distance (0%–38.18% in M1) than sub-elite weightlifters during Phase M1. This finding is supported by Ikeda et al., who found that high-performing weightlifters often adopt lower positions (lower COG and closer DCC vertical distance) during Phase M1[15]. The movement of the barbell away from the weightlifter during the first pull of Phase M1 is related to poorer weightlifting performance [23,27]. The increase in barbell mass does not affect the absolute mechanical work and power output during the first pull of Phase M1; a lower position can increase the mechanical work performed by the weightlifter during Phase M1 [5]. In addition, the proportion of time spent in each phase in our study suggests that elite weightlifters spent a significantly higher proportion of time in Phase M1 than sub-elite weightlifters. Phase M1 is primarily focused on absolute strength, placing higher demands on the athlete's lower limb extensors [4]. High-level weightlifters tend to adopt an optimal sequence of phase coordination patterns, with significantly higher execution times in the positive acceleration phase of the barbell than sub-elite weightlifters [28,29]. Considering the lower COG, closer DCC vertical distance, and higher proportion of time spent in Phase M1 by elite weightlifters, we speculate that elite weightlifters can apply positive acceleration to the barbell for a longer period and greater distance during Phase M1.

Phase M2 is also known as the transition phase, during which athletes store elastic potential energy in the lower limb muscles, which enables them to release explosive force in Phase M3 [11,26]. During this phase, the vertical velocity loss of the barbell must be minimized as much as possible to avoid generating negative momentum and reduce unnecessary energy consumption, which is a key indicator of an excellent weightlifter [4, 8]. Liu et al. proposed that the DCC is a critical indicator for evaluating the application of muscle strength and assessing snatch stability [13]. In the results of this study, we also found that elite athletes exhibited a smaller vertical DCC distance compared to sub-elite athletes. Using the torque formula $M=F \times r$, where M represents torque, F is the gravitational force exerted by the barbell, and r is the moment arm formed by the vertical DCC. Elite athletes optimized their posture and technique to reduce the length of the moment arm, thereby decreasing the required torque and enhancing lifting efficiency. This suggests that elite athletes demonstrate greater snatch stability and reduced energy expenditure during the M2 phase.

Phases M1 and M3 correspond to the previously studied "The first pull" and "The second pull," during which the two pulls provide upward acceleration to the barbell, which then reaches its highest point [26]. The pull force in Phase M1 is relatively slow and can be considered strength-oriented, while the pull force in Phase M2 is faster and can be considered power-oriented [4,9]. In this study, elite athletes had significantly smaller knee extension angles and COG than sub-elite athletes in the two phases. Apart from the lower COG in Phase M1 [15], previous studies did not find this phenomenon of smaller knee extension angles [13,15], which is possibly due to numerical differences occurring in Phase M1 ranging from 35.82% to 78.45% and Phase M3 ranging from 17.47% to 24.74%, 30.92% to 49.38%, and 50.93% to 65.85% (a series of 1D numerical differences). They did not appear at discrete numerical points in previous studies of Phases M1 and M3. As a result, such differences occur. A study comparing the biomechanics of two different lifting techniques (squatting and bending over) found that more flexed knee joints during deep squat lifting result in greater hip–

ankle joint extension torque [30]. Both studies found that smaller knee joint extension angles during closed-chain squat-stand tasks lead to greater extension torque in lower limb joints. Lower limb extension torque is crucial for increasing the vertical speed of the barbell; the explosive extension of the lower limb joints generates lower limb extension torque acting on the barbell, which results in maximum barbell speed at the end of Phase M3 [11]. Therefore, we speculate that the smaller knee joint extension angles observed in elite athletes during Phases M1 and M3 enable greater lower limb extension torque to act on the barbell, which allows the barbell to gain more upward momentum. In Phase M4, we also found a phenomenon similar to Phases M1 and M3, where elite athletes exhibited greater knee flexion angles. However, unlike the mechanisms in Phases M1 and M3, Phase M4 requires faster and deeper descent under the barbell, which leads to rapid knee joint flexion [11]. Elite athletes in this study also exhibited greater knee flexion angles in Phase M4, which effectively reduces the rapid descent of knee joint squat positions to the appropriate receiving position for the barbell. The lower COG in Phase M3 and the greater knee flexion angles in Phase M4 indirectly confirm that excellent weightlifters spend much less time in Phase M4 [31].

Chiu et al. found that better-performing weightlifters tend to pull the barbell to a higher position (maximum height) for achieving greater vertical displacement, which suggests that proficient weightlifters excel in using higher barbell displacement buffering techniques to successfully catch heavier barbells [23]. However, a study employing binary functional principal component analysis of barbell trajectories refutes this speculation by reporting no correlation between maximum barbell height and weightlifting performance or biomechanics [32]. Many unsuccessful snatches are dropped from the receiving position (Phase M5), and the trajectories of unsuccessful snatches are similar to successful ones in the first four phases [32]. Our study results clearly support the latter finding: a significant difference in snatch performance is observed between elite and sub-elite weightlifters, but no significant difference exists in the maximum vertical height of the barbell. This phenomenon occurs under the premise that weightlifters must lift the barbell to a critical minimum height to have sufficient time to descend under the barbell [3,33]. Ikeda et al. found that adopting a lower receiving position in Phase M5 can increase the distance of receiving and thus enhance the receiving performance of sub-elite Japanese female weightlifters [15]. Our study results align with theirs: elite weightlifters have a lower COG in Phase M5 despite no difference in maximum barbell height, which indicates better receiving performance with longer receiving distances. In addition, the ability to brake the barbell during the descent phase (Phases M5–M6) is crucial. A proficient weightlifter needs a lower body COG to catch the barbell and resist the downward momentum for stabilizing the barbell overhead and preventing it from falling forward [3]. Our study results also demonstrate that elite weightlifters exhibit better braking abilities in Phases M5 and M6, which are characterized by greater upward vertical acceleration of the barbell in Phase M5 and slower barbell descent in Phase M6. Overall, elite weightlifters show good abilities in braking the barbell's descent and receiving performance in Phases M5–M6.

Some limitations of our study need to be considered: we only investigated weightlifters from China, and snatch techniques may vary slightly across different regions[34], which could influence the generalizability of our results. Secondly, this study focused exclusively on male athletes in the 73 kg weight class, which presents a limitation as it does not account for potential differences between genders or among various weight categories. Moreover, our study analyzed only 20 athletes due to the limited sample size. Future research should expand to athletes from more regions and increase the sample size for broader insights.

5. Conclusion

This study indicates that elite weightlifters exhibit specific biomechanical advantages during various phases of the snatch:

1) In Phase M1, elite athletes show a lower COG, a closer DCC vertical distance (lower position), and a larger proportion of time used to increase the distance and duration over which they perform work on the barbell.

2) In Phase M2, elite athletes reduce energy consumption during barbell ascent by using a closer DCC vertical distance.

3) Greater knee flexion angles in Phases M1 and M3 increase lower limb extension torque, which enables the barbell to achieve greater upward power.

4) Lower knee joint extension angles in Phase M4 indicate that elite athletes have faster squat-to-catch speeds.

5) During Phases M5–M6, elite athletes demonstrate excellent abilities in controlling the barbell descent and accurate squat-to-catch capabilities.

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Ethical approval: The contents and methods of this study have been deemed legally valid and approved by the Ethics Committee of Zhejiang Normal University in May 2023(No. ZSRT2023078). The requirement for informed consent was waived by the Ethics Committee of Zhejiang Normal University, as all video data were obtained from open competitions with no intervention, and the video capture method used did not affect the athletes' performance in any way. Our research adhered to the principles of the Declaration of Helsinki.

Conflict of interest: The author declares no conflict of interest.

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