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Inter- and intra-individual variability in the kinematics of the back squat

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ABSTRACT

The purpose of this study was to explore the level of inter- and intra-individual variability in the kinematic profiles of the back squat movement among skilled weightlifters. Ten competitive weightlifters volunteered for participation in this study. Barbell velocity ($V_{Barbell}$) and angular velocity of the ankle (ω_{Ankle}), knee (ω_{Knee}) and hip joint (ω_{Hip}) were obtained by kinematic recording of six trials at 90% of 1RM in the back squat. Inter-individual variability was assessed by analysing inter-individual differences in the velocity curves through the statistical parametric mapping method. Intra-individual variability was assessed through a correlation analysis between the barbell velocity curves of each trial for each participant. Partial least squares regression analysis, was performed to relate changes in intra-individual variability to movement and anthropometric characteristics. Significant inter- and intra-individual differences were identified in $V_{Barbell}$, ω_{Ankle}, ω_{Knee}, and ω_{Hip} ($p \leq 0.05$). Having a short trunk and thigh, and a long shin in combination with greater anterior-posterior displacement of the barbell and slower velocities during the acceleration phase increased intra-individual movement consistency over movement variability. The results of the present study clearly demonstrate that skilled weightlifters display both significant inter- and intra-individual variability in the successful execution of the back squat.

1. Introduction

The back squat is one of three lifts being performed in the competitive sport of powerlifting, and one of the most widely used strength training exercises for the lower body. The back squat movement, as well as any other human movement, can be considered to be the integrated end product of the neuromuscular control of the musculoskeletal system, and therefore the dynamics of the back squat exercise under different circumstances has been quite thoroughly investigated in the past. For instance, significant differences in net muscle moments and joint angles of the hip, knee and ankle joints have previously been documented during squatting with a narrow, medium and wide stance (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001). Similarly, it has been shown that restricting the forward travel of the knees during squatting, increases the torque produced at the hip joint, and decreases the torque produced at the knee joint compared to a squat with no restrictions on knee travel (Fry, Smith, & Schilling, 2003). Further, the application of different exercise variations of the back squat, such as the powerlifting style squat and the box squat also changes the kinematics of the lift significantly (Swinton, Stewart, Lloyd, Keogh, & Agouris, 2012). Together these results indicate that the individually adopted technical style applied during the back squat, may have a major impact on the net muscle moments produced at

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each joint as well as the kinematics of the movement.

However, inter-individual differences in levels of joint mobility, anthropometric characteristics, muscle architecture, technical proficiency and muscular strengths and weaknesses have not been taken into account in the above mentioned studies, and as such, the optimal configuration of these variables (exercise variation, stance width and knee travel) may be individually specific if the aim is to maximize performance. Inter-individual differences have previously been documented in skilled competitive collegiate powerlifters. More specifically, skilled competitive collegiate powerlifters have been shown to display significantly longer time to descent and significantly higher knee peak angular velocity between the bottom of the lift and the sticking point compared to competitive high school powerlifters and novice powerlifters (Miletello, Beam, & Cooper, 2009). These results are further supported by the work of McLaughlin et al. that also show a longer descent time in world-class powerlifters as compared to less skilled powerlifters (McLaughlin, Dillman, & Lardner, 1977). Collectively, this points towards the importance of acknowledging inter-individual differences in the execution of the back squat exercise, as this may contain important information that can be used in the process of performance optimization. This is underlined by the work of Flanagan, Kulik, and Salem (2015) who showed that a limiting joint may exist in back squat performed to failure, and that the limiting joint was specific for each individual participant, with participants failing either because of insufficient force production at the hip joint or at the knee joint (Flanagan et al., 2015). In that study single participant data was examined as opposed to the normal practice of examining group mean data. It is therefore evident that the use of group mean data analysis may preclude the analysis of important inter-individual differences in lifting kinematics, which may result in different lifting strategies across individuals. Therefore, we believe that significant inter-individual differences may be present in the kinematics of the back squat in trained individuals.

Moreover, the back squat movement may be considered a relatively simple movement, seeing, as the number of degrees of freedom is very limited due to certain passive constraints. The passive constraints in the back squat entail the vertical movement pattern being determined largely by the inertia of the weight being lifted and the influence of gravity, combined with the relatively simple geometry of the musculoskeletal system (constituted by four body segments and three joints during back squat). Intuitively, one could assume that the "degrees of freedom problem" as defined by Bernstein (1967), does not pose a significant impact during this type of movement and as a consequence that for any one person the movement variability from trial to trial is very limited. However, the back squat is a bilateral, multi-joint, dynamic movement, which recruit most of the musculature in the lower body. Also, as considerable activation is required from the muscles involved in postural stabilization of the trunk (Schoenfeld, 2010), it has been estimated that more than 200 muscles are activated during the execution of the back squat (Solomonow et al., 1987). Optimal performance in the back squat thus requires the coordinated timing and activation of all involved muscles. The expression of maximal strength levels in the squat exercise, as well as any other multi-joint dynamic exercise, can therefore be viewed as a skilled act, in which the coordinated activation and timing of all the involved agonist, synergist and antagonist muscles are of paramount importance (Sale, MacDougall, Upton, & McComas, 1983). As a result, we believe that the back squat is a complex movement, which is also subject to Bernsteins "degree of freedom" problem, and that significant intra-individual variability is present in the movement from trial to trial even in highly trained individuals.

Thus, the primary purpose of this study was to explore the levels of both inter- and intra-individual variability in the kinematics of the back squat movement among skilled weightlifters. This was accomplished by analysing inter-individual differences in the velocity curves of the barbell, and the angular velocity curves of the ankle, knee, and hip joint, as well as performing correlation analysis of the velocity profiles between all trials for each participant, and then dividing participants in to two groups based on their average correlation coefficients, respectively. We hypothesized that in spite of their advanced skill level, skilled weightlifters will demonstrate significant inter- and intra-individual variability in lifting strategies represented by the kinematic profiles applied during the performance of a heavy back squat.

2. Methods

2.1. Participants

Ten healthy males (age: 26.5 ± 5.9 years (mean ± SD), height: 1.83 ± 0.08 m, body mass: 90.9 ± 16.6 kg, one repetition maximum (1RM) in back squat: 165.5 ± 27.0 kg, resistance training experience: 8.4 ± 4.3 years) volunteered to participate in this study. All the participants were competitive weightlifters with at least four years training experience with the back squat exercise prior to enrolment in the study, and could safely squat below parallel (i.e. the crease of the hip below the top of knee). None of the participants had any history of neuromuscular disorders or injuries in the lower extremities. The study was approved by the local ethics committee of the North Denmark region, and all participants signed a written informed consent after having been explained the experimental methods and risks, both verbally and in writing.

2.2. Experimental approach

To investigate the inter- and intra-individual variability in the kinematics of the back squat exercise the participants performed a 1RM test, followed by a total of six single repetition trials at 90% of their newly established 1RM. The lifting load of 90% was chosen to as accurately as possible reflect the dynamic characteristics of a 1RM trial, while concurrently permitting the performance of several lifts for assessment of inter- and intra-individual variability.

Data collection: Three-dimensional kinematics was collected at 120 Hz using an 8-camera Qualisys motion analysis system (Oqus 300/310, Qualisys AB, Gothenburg, Sweden). System calibration was completed prior to data acquisition of each participant, using the standard calibration practices outlined by the Qualisys user manual. Calibration was accepted if average 3D residuals were estimated to be ≤ 1.0 mm.

Following the system calibration, participants wore a set of 33 reflective spherical markers (11 mm diameter) for the recording of a standing reference trial to determine the segmental coordinate systems, joint axes and anatomical positions. For the reference trial, markers were placed on the right heel, lateral and medial malleolus, lateral and medial metatarsophalangeal joints, the medial and lateral femoral epicondyles, the right greater trochanter, right and left anterior superior iliac spines, right and left posterior superior iliac spines, right and left acromion and both ends of the barbell, respectively. Furthermore, semi-rigid plastic plates with a cluster of three tracking markers were secured to the right shank and thighs and on the sacrum, and on the upper back. Prior to initiating the data collection for the 1RM and the six trials at 90% of 1RM, the markers were removed from the medial malleolus, medial metatarsophalangeal joint, the medial and lateral femoral epicondyles, greater trochanter, right and left anterior superior iliac spines, right and left posterior superior iliac spines, lateral and medial acromion respectively.

Prior to testing, participants performed a general and a specific warm up, based on their estimated 1RM in accordance with (Brown & Weir, 2001). Following the warm up, three attempts were performed at 80%, 90%, and 100% of their estimated 1RM. During the rest periods, the participants were asked to indicate their rate of perceived exertion (RPE) using a resistance exercise-specific scale ranging from 1 to 10 (Zourdos et al., 2016), with 1 and 10 being minimal and maximal exertion, respectively. The RPE scale was used to evaluate the self-perceived exertion of each lift and to ensure that each participant had exerted themselves maximally. If the predicted 1RM was not perceived as RPE = 10, the weight was increased by 2.5–10 kg subsequently. If the participants failed to lift their predicted 1RM the weight was reduced by 2.5–10 kg until the true 1RM was established.

Following the completion of a successful 1RM, all participants performed six single repetition sets at 90% of the newly established 1RM. A rest period of four to seven minutes was provided between sets to limit the confounding influence of accumulated fatigue. All lifts were performed starting from an erect position from which the lifter descended until the crease of the hip at the hip joint was below the top of the knee to ensure approximately similar range of motion between participants. When the desired range of motion was achieved, the lifter reversed the action and ascended back to the erect position. If squatting depth requirements were not met, the trial was repeated.

2.3. Data processing

Visual3D motion (Version 4.21, C-Motion Inc., Germantown, Maryland, USA) was used for initial processing of the kinematic data. All marker-data were filtered using a 4th order Butterworth bi-directional low-pass filter with a cut-off frequency of 6 Hz. The following variables were calculated for each trial: vertical barbell velocity ($V_{Barbell}$), angular velocity in the ankle (ω_{Ankle}), knee (ω_{Knee}), and hip joints (ω_{Hip}). All kinematic data were then exported to MATLAB (Version R2015B, MathWorks Inc, Natick, Massachusetts, USA) for subsequent data processing. Then, the range of frames recorded for each trial, defined as the period between the onset of vertical barbell descent to the completion of vertical barbell ascent, was isolated and resampled to 100 points (i.e. the movement time was normalized to 100%).

To separate the important features during the back squat movement, the squat cycle was divided into five lifting phases as previously described (Escamilla et al., 2001). I) descent phase (DES), defined from the onset of the descent to the onset of positive barbell velocity; II) acceleration phase (AP), defined from the end of DES to the first positive peak in the barbell velocity; III) sticking region (SR) defined from the end of AP to nearest local minimum; IV) maximum strength region (MSR) defined from the end of SR to the second peak in the barbell velocity; and V) deceleration phase (DP), defined from the end of MSR to lift completion. Relative duration of each phase was computed for DES, AP, SR and MSR, respectively.

To verify that the data obtained at 90% of 1RM was representative of the movement characteristics obtained in the 1RM trial a correlation analysis was performed. Basically, for each individual subject, the barbell velocity curves from the six trials at 90% of 1RM were correlated with the barbell velocity curve of the 1RM trial one at a time, yielding six correlation coefficients (CC) per subject. For this procedure, a time normalization approach was applied in which the eccentric phase and concentric phase was normalized to 50% each.

Further, ten independent variables descriptive of either the movement characteristics or anthropometric characteristics of the individual participants were extracted for use in a regression analysis. The following variables were extracted from each trial and averaged across the six trials for each participant: Maximal anterior-posterior horizontal displacement of the barbell during the squat cycle, maximal range of motion of the hip, knee and ankle joint, mean vertical velocity during the AP phase, mean vertical acceleration and peak accelerations during the AP phase, Horizontal distance between barbell and hip joint, thigh length, and shin length.

2.4. Statistics

The normal practice in statistical analysis of biomechanical data, involves *ad* hoc scalar extraction of key elements or features in the dataset. However, this approach greatly reduces the complexity of the original highly multivariate data set, while simultaneously only considering specific portions of the data set. One way to preserve the complexity of the dataset and to integrate the entire dataset in the statistical analysis is to apply a method called statistical parametric mapping (SPM). SPM uses random field theory to assess the field wide significance of a statistical map, and thus to objectively identify field regions that co-vary significantly (Pataky, Robinson, & Vanrenterghem, 2013). Therefore, inter-individual variability were assessed by analysing inter-individual differences in the velocity curves of $V_{Barbell}$, ω_{Ankle}, ω_{Knee}, and ω_{Hip} through a one way analysis of variance (ANOVA) using the statistical parametric mapping method (SPM). To assess intra-individual variability, two different analyses were performed. First, we performed a Pearson product-moment correlation analysis of the barbell velocity profile between the six trials performed at 90% of 1RM for each participant. This yielded a total of 15 CĆs, indicative of the overall similarity of barbell velocity profiles across trials for each participant. The CC's were interpreted using the following intervals: weak correlation (< 0.5), moderate correlation (0.5–0.7), good correlation (0.7–0.9), very good correlation (> 0.9) (Mukaka, 2012). As a further analysis of inter-individual variability, we performed a one-way ANOVA with a Tukey post hoc test, to test for individual differences in the obtained CC's between participants. The second test of intra-individual variability was comprised of computing the mean barbell velocity profile of the six trials of each individual participant and the corresponding standard deviation for each time point along the profile. The profile was then divided into the five lifting phases, DES, AP, SR, MSR, and DP. The pool of standard deviation values of each phase is indicative of the intra-individual variability of the data during that particular phase. Therefore, we compared the standard deviation values of each phase to the other phases using a one-way ANOVA with a Tukey post hoc test, to identify differences in intra-individual variability across the lifting phases. For the CĆs obtained when comparing the trials at 90% of 1RM to the 1RM trial a Kruskall-Wallis test with a Tukey post hoc test was applied to test for differences between subjects.

For the regression analysis a partial least squares regression analysis was performed to identify any predictors of intra-individual movement variability. This particular analysis was chosen as the dataset exhibited multicollinearity, and as the number of independent variables equalled the number of samples, thus violating the assumptions for using a multiple regression analysis. The dependent variable was the mean CC of the barbell velocity profiles calculated between the six trials for each individual. The ten descriptive variables of the individual movement or anthropometric characteristics served as independent variables. In the instance that any of the independent variables displayed a low value (< 0.8) in the model parameter "variable importance in the projection" or the regression parameter was close to 0 (< 0.1) the variable(s) were removed and the model was rerun. Statistical significance was accepted at $p \leq 0.05$. All statistical procedures were performed in MATLAB (Version R2015b, MathWorks Inc, Natick, Massachusetts, USA), except for the partial least squares regression analysis which was performed in SPSS (Version 25.0, IBM Corp., Armonk, NY, USA).

3. Results

All participants completed the 1RM test (165.5 ± 27.0 kg) and the six trials at 90% of 1RM. It was possible to identify all five lifting phases in all trials. The mean duration of each of the 5 phases over the six trials for each participant, as well as group means of all trials are presented in Fig. 1. As indicated by the CC values (≥0.87) in Table 1, the trials obtained at 90% of 1RM were good to very good correlated with the 1RM trial (Mean CC = 0.94 ± 0.05). However, the CC values obtained for participant 2 were significantly lower than those obtained for participant 4 ($p = 0.009$) and 5 ($p = 0.016$), respectively.

Applying the SPM procedure revealed significant inter-individual differences in $V_{Barbell}$, ω_{Ankle}, ω_{Knee}, and ω_{Hip} throughout most of the lifting phases, as can be seen in Fig. 2. The only instances where the significance level was not reached for $V_{Barbell}$, was at the end of the DES phase, at the converging point between the SR and MSR phases and during the DP phase. For ω_{Ankle}, the significance level was not reached at the end of DES, SR and DP, respectively. For ω_{Knee} and ω_{Hip}, the significance level was not reached at the beginning and end of DES and at the end of DP. The results of the Pearson product-moment correlation analysis of the barbell velocity profile for the six trials of each participant are presented in Table 2. Using the average CC's it was possible to the divide the participants in to two groups. One group that exhibited good correlation on average (CC between 0.7 and 0.9) (Pertaining to six participants) and one group that exhibited very good correlation (CC > 0.9) (Pertaining to four participants). Barbell velocities from one representative participant from each of the two subgroups are depicted in Fig. 3. In most cases the participants in each group were significantly different from the participants in the opposite group ($p \leq 0.05$), as shown in Table 2.

In Table 2, none of the participants attained a mean CC-value of 1 in the inter-trial comparison of barbell velocity profiles, indicating that trials were not reproduced perfectly. The minimum and maximum CC's presented in Table 2, further indicates that some trials may have been very similar, while others were very different. To illustrate this point, P10 had a minimum and maximum CC of 0.49 and 0.99, respectively.

The standard deviations of each lifting phase of the vertical barbell velocity profile for each participant, further illustrated significant intra-individual variability in the data set, as presented in Table 3. All participants demonstrated significant differences between lifting phases, indicating that the intra-individual variability was significantly greater in some phases than in others. In general, the highest standard deviations were obtained in the AP and DP phases, and these were in most cases significantly different from the other phases ($p \leq 0.05$).

To further underline the finding that considerable intra-individual variability existed in the data set, all six trials of a single participant (P3) are presented in Fig. 4. This particular participant completed the six trials using two different strategies, one with a slow descent and one with a faster descent. The two strategies were used interchangeably throughout the trials.

In the partial least squares regression analysis, five independent variables (mean and peak acceleration during the AP phase, range of motion in the hip, knee and ankle) were removed from the model due to either low regression parameters or low values in the "variable importance in the projection" parameter. Through extraction of five latent factors, the model was capable of explaining 100% of the variance in the independent variables, which in turn yielded a r^2-value of 88.2%. The regression coefficients for each of the independent variables were as follows: Distance from barbell to hip joint −4.46, thigh length −0.30, shin length 3.98, mean anterior-posterior displacement of the barbell 4.23, and mean velocity during the AP phase −0.67, respectively. Thigh length (1.454 and 1.325) and shin length (1.406 and 1.270) were rated as the two most important variables in latent factor 1 and 2, while barbell to hip joint distance (1.644) and mean anterior-posterior displacement of the barbell (1.279) was rated highest for latent factor 3. For latent factor 4 and 5, barbell to hip joint distance (1.584 and 1.579) and shin length (1.232 and 1.423) were again rated as the two

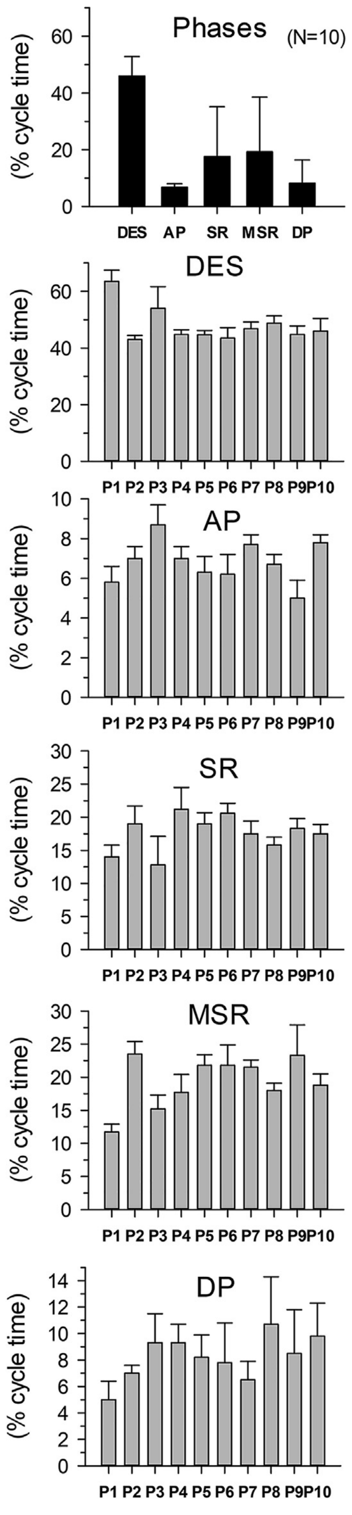

Fig. 1. The mean duration of each of the 5 lifting phases over the six trials, presented as group mean in the upper illustration, and for each participant in each of the 5 phases in the below illustrations. Error bars indicate standard deviation. DES = descent phase, AP = acceleration phase SR = sticking region MSR = maximum strength region, DP = deceleration phase. N = 10.

Table 1
Correlation coefficients of the barbell velocity profile between each of the six trials obtained at 90% of 1RM and the 1RM trial.

Trial	1	2	3	4	5	6	Mean
P1	0.98	0.96	0.86	0.94	0.96	0.97	0.95
P2	0.88	0.90	0.73	0.90	0.90	0.90	0.87
P3	0.98	0.96	0.96	0.96	0.97	0.97	0.97
P4	0.97	0.98	0.90	0.99	0.99	0.99	0.97[a]
P5	0.97	0.98	0.91	0.99	0.99	0.97	0.97[a]
P6	0.95	0.95	0.84	0.94	0.95	0.98	0.93
P7	0.97	0.95	0.88	0.97	0.98	0.95	0.95
P8	0.93	0.93	0.83	0.92	0.94	0.97	0.92
P9	0.93	0.95	0.84	0.96	0.96	0.96	0.93
P10	0.96	0.98	0.84	0.96	0.97	0.98	0.95

Pearson product-moment correlation analysis of the barbell velocity profile between each of the six trials obtained at 90% of 1RM and the 1RM trial. Correlation Coefficient intervals: weak (< 0.5); moderate (0.5–0.7); good (0.7–0.9); very good (> 0.9). a = significantly different from P2.

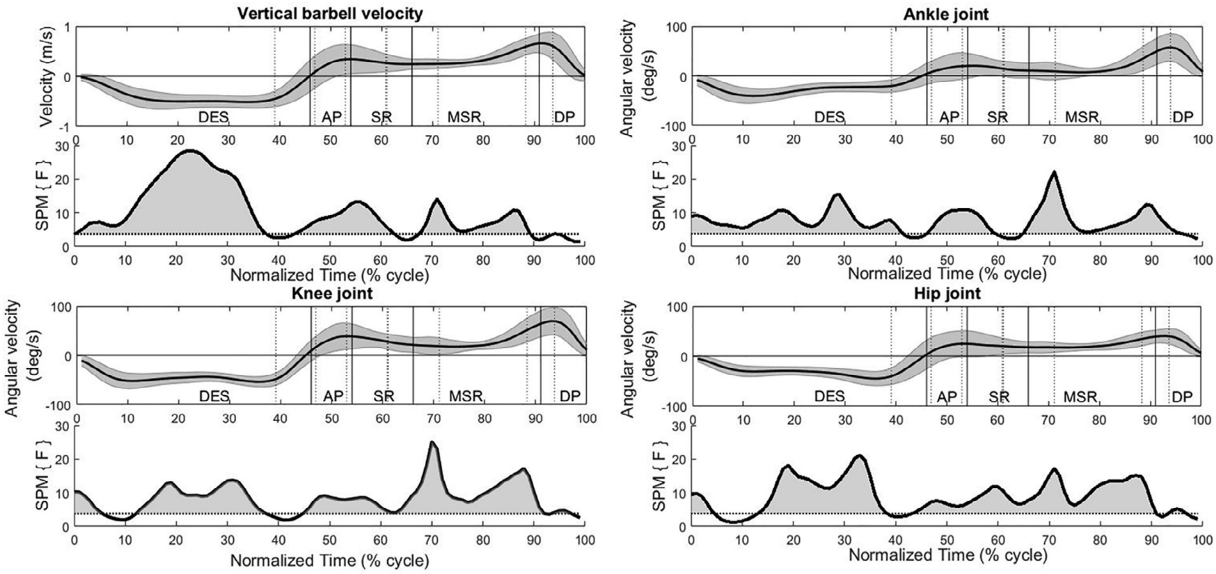

Fig. 2. Velocity profiles and results of the statistical parametric mapping procedure for the barbell, ankle joint, knee joint, and hip joint. In the velocity profiles, the thick black line represents the mean profile, while the shaded grey area represents the standard deviation. The vertical solid black lines represent the mean start and end of each lifting phase while the vertical dotted black lines represent the standard deviations of the start and end of each phase. In the statistical parametric mapping figures, the horizontal black dotted line represents the critical F-value threshold. The grey area under the black line represents the portions of the movement where significant differences reside between participants. DES = descent phase, AP = acceleration phase SR = sticking region MSR = maximum strength region, DP = deceleration phase. N = 10.

most important variables.

4. Discussion

In this study, we investigated barbell and joint kinematics of the back squat exercise in ten skilled weightlifters performing six separate lifts at 90% of their 1RM. We showed significant inter- and intra-individual variability in all investigated kinematic parameters, suggesting that the back squat movement is variable between participants, and can be performed successfully even at very high lifting loads using variable lifting strategies. Generally, the current results support our initial hypothesis that even trained weightlifters would demonstrate significant inter- and intra-individual variability in the lifting strategies applied during the performance of a heavy back squat.

All participants demonstrated a clear double peak in vertical barbell velocity during the concentric phase and achieved the maximum vertical barbell velocity at the second peak, which is similar to previous results (Escamilla et al., 2001; McLaughlin et al., 1977). Similarly, when we correlated the trials obtained at 90% of 1RM with the 1RM trial, we found good to very good correlation coefficients. This indicates that kinematic profiles obtained at a load of 90% 1RM can be considered to represent the kinematic profiles of lifts with a load of 100% of 1RM.

Vertical barbell velocity exhibited inter-individual variability throughout most of the five lifting phases. This indicates that the participants utilized significantly different lifting strategies, when compared to each other, in order to achieve the goal of successful

Table 2
Mean correlation coefficient of the barbell velocity profile between trials for each subject.

	CC (mean ± SD)	[min:max]	Statistical difference
P1	0.86 ± 0.10	[0.63:0.98]	b, d, e
P2	0.98 ± 0.01	[0.94:0.99]	a, c, h, I, j
P3	0.79 ± 0.15	[0.60:0.98]	b, d, e, g
P4	0.97 ± 0.02	[0.93:0.99]	a, c, h, j
P5	0.97 ± 0.02	[0.92:0.99]	a, c, h, I, j
P6	0.89 ± 0.09	[0.70:0.98]	
P7	0.94 ± 0.04	[0.84:0.99]	c, j
P8	0.85 ± 0.12	[0.62:0.99]	b, d, e
P9	0.87 ± 0.08	[0.73:0.97]	b, e
P10	0.84 ± 0.14	[0.49:0.99]	b, d, e, g

Pearson product-moment correlation analysis of the barbell velocity profile between each and every one of the trials performed at 90% of 1RM for each participant. Correlation Coefficient intervals: weak (< 0.5); moderate (0.5–0.7); good (0.7–0.9); very good (> 0.9). a = significantly different from P1, b = significantly different from P2, c = significantly different from P3, d = significantly different from P4, e = significantly different from P5, f = significantly different from P6, g = significantly different from P7, h = significantly different from P8, I = significantly different from P9, j = significantly different from P10.

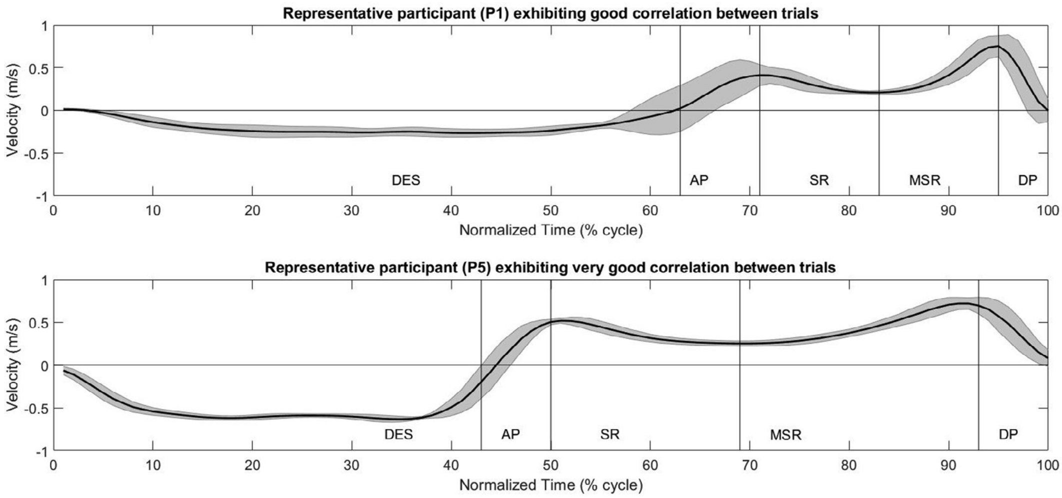

Fig. 3. Velocity profile for the barbell of a representative participant exhibiting good correlation between trails and a representative participant exhibiting very good correlation between trails. The thick black line represents the mean profile, while the shaded grey area represents the standard deviation. The vertical solid black lines represent the mean start and end of each lifting phase. DES = descent phase, AP = acceleration phase SR = sticking region MSR = maximum strength region, DP = deceleration phase.

lifting at 90% of 1RM. There were, however, three instances in barbell velocity where there were no significant difference between participants, namely at the end of the DES phase, at the converging point between SR and MSR and during DP. This can most likely be explained by the fact that at the end of the DES and DP phase the barbell decelerates as it approaches zero velocity, either just before the beginning of the ascent phase or when the barbell comes to a stop at the fully extended position. Similarly, the converging point between the SR and MSR represents the point of minimum velocity between the first and second local peak during the ascent phase, also known as the "sticking point". It therefore seems that these three occasions during the back squat remain relatively fixed across participants, while considerable inter-individual differences can be observed in the rest of the movement. The same three fixed occasions, displaying no evidence of inter-individual difference, are evident in the angular velocity pattern of the ankle. For the hip and knee, however, the fixed occasion displaying no evidence of inter-individual difference, located at the converging point between the SR and MSR phases is not present. This may indicate that the participants are utilizing different strategies related to the angular velocity of the hip and knee to overcome the sticking point. For the hip and knee, a new fixed occasion with no significant inter-individual differences is instead present in the beginning of the DES phase. This can most likely be explained by the fact that at the beginning of the back squat exercise considerable movement must occur at both the hip and knee joint in order for the descent phase to be successful.

The inter-individual differences in lifting pattern observed in this study may be explained by differences in joint mobility, anthropometric characteristics, technical proficiency, skill level and muscular strengths and weaknesses, which inherently cause each individual to lift in their own way. Similar inter-individual differences have previously been reported in the kinematics of elite javelin throwers during competition performance, suggesting that high-level performance can be achieved using a multitude of different biomechanical solutions (Bartlett, Müller, Lindinger, Brunner, & Morriss, 1996; Campos, 2004). It should be noted that the presence

Table 3
Mean standard deviation (SD) of vertical barbell velocity for DEC, AP, SR, MSR and DP.

	DES (m/s)	AP (m/s)	SR (m/s)	MSR (m/s)	DP (m/s)	Overall significance
P1, mean SD	0.07 (b,e)	0.23 (a,c,d)	0.07 (b,e)	0.09 (b,e)	0.23 (a,c,d)	λ
SD	0.0523	0.0477	0.0379	0.0494	0.0873	
P2, mean SD	0.07 (c,d)	0.11 (c,d)	0.04 (a,b)	0.04 (a,b,e)	0.08 (d)	λ
SD	0.0569	0.0610	0.0193	0.0134	0.0378	
P3, mean SD	0.17 (c,d)	0.16	0.05 (a,e)	0.08 (a,e)	0.20 (c,d)	λ
SD	0.1140	0.1241	0.0112	0.0494	0.0622	
P4, mean SD	0.06 (c,e)	0.10 (c,d,e)	0.03 (a,b,e)	0.03 (b,e)	0.15 (a,b,c,d)	λ
SD	0.0405	0.0516	0.0090	0.0248	0.0559	
P5, mean SD	0.05 (b,e)	0.12 (a,c,d)	0.04 (b,e)	0.07 (b,e)	0.13 (a,c,d)	λ
SD	0.0452	0.0741	0.0144	0.0211	0.0506	
P6, mean SD	0.11	0.17	0.09 (e)	0.10	0.18 (c)	λ
SD	0.1036	0.0699	0.0224	0.0313	0.0509	
P7, mean SD	0.11 (b)	0.17 (a,c,d)	0.07 (b)	0.07 (b)	0.14	λ
SD	0.0744	0.1068	0.0205	0.0293	0.0601	
P8, mean SD	0.07 (b,d,e)	0.26 (a,c,d)	0.08 (b,e)	0.14 (a,b,e)	0.35 (a,c,d)	λ
SD	0.0742	0.1063	0.0326	0.0683	0.1243	
P9, mean SD	0.09 (b)	0.24 (a,c,d)	0.10 (b)	0.06 (b,e)	0.16 (d)	λ
SD	0.1021	0.1429	0.0361	0.0285	0.0653	
P10, mean SD	0.13 (b,e)	0.32 (a,c,d)	0.10 (b,e)	0.08 (b,e)	0.13 (a,c,d)	λ
SD	0.1139	0.0925	0.0252	0.0372	0.1155	

Significant differences $p \leq 0.05$: λ) overall significant difference in vertical barbell velocity SD between lifting phases. a) Significantly different from DES, b) significantly different from AP, c) significantly different from SR, d) significantly different from MSR, e) significantly different from DP. DES = descent phase, AP = acceleration phase, SR = sticking region, MSR = maximum strength region, DP = deceleration phase.

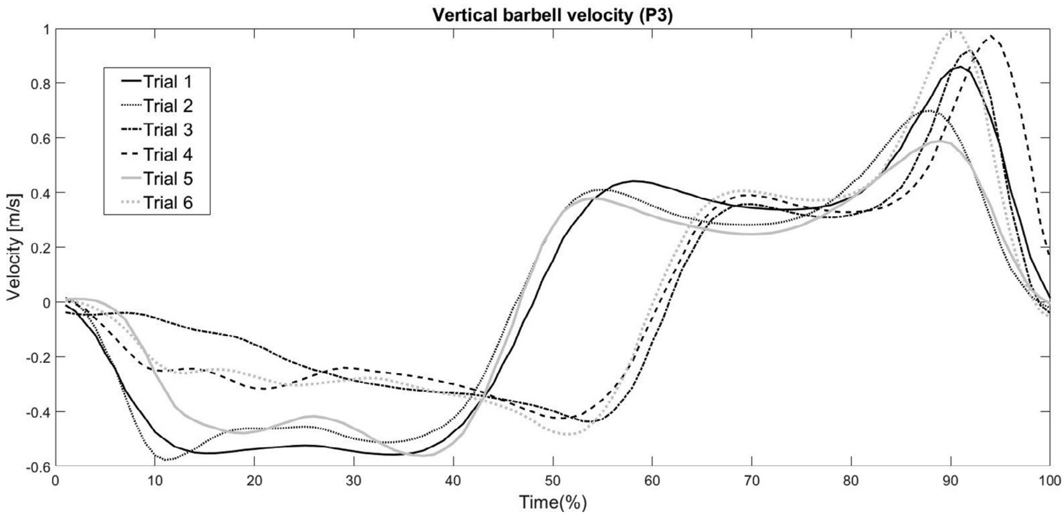

Fig. 4. Velocity profile for the barbell of one participant who completed the six trials using two different strategies, one with a slow descent and one with a faster descent. The two strategies were used interchangeably throughout the trials.

of inter-individual differences does not necessarily mean that each participant has achieved the optimal lifting strategy based on their individual characteristics, as it is beyond the methods of this study to contemplate on the effectiveness of the movement of each individual participant.

Significant intra-individual differences were also present in this study, illustrated by the CC-values presented in Table 2. The minimum and maximum CC-values presented for each participant, clearly indicate that some trials were very similar while other trials were not, despite the overall margin of error for the lift being relative small, considering the high lifting load of 90% of 1RM. This suggests that successful lifting at 90% of 1RM can be achieved using different biomechanical solutions or lifting strategies that exploit the redundancy of the musculoskeletal system (Latash, 2012), and again underlines the fact that even trained participants does not produce identical movement patterns even at high lifting loads.

The standard deviations of each lifting phase of the vertical barbell velocity profile for each participant illustrated in Table 3, further illustrated significant intra-individual variability across the lifting phases of each participant. Overall, the AP and DP phases were the most variable. A possible explanation for the variability in the AP phase may be related to the descending phase preceding the acceleration phase, as well as the timing related to the transition from descent to ascent during the stretch-shortening cycle (SSC). A SSC during the back squat requires sufficient force to reduce the eccentric velocity of the load to zero, prior to beginning the concentric action (Frost, Cronin, & Newton, 2010). Such change in momentum is directly proportional to the change in velocity and the mass of the load. This change in momentum is also proportional to the force that is causing such a change, and the duration over which the change takes place. Thus, variability in the duration of the descending phase, as shown in Fig. 1, would have a profound impact on the SSC during the descent-ascent transition and hence, squatting kinematics during the acceleration phase. The variability in the DP phase could be explained by the fact that some participants may have voluntarily decreased muscular force production once past the sticking point in an attempt to conserve energy, whereas others may have sought to extend as forcefully as possible when completing the lift.

The partial least squares regression analysis revealed that a negative relationship existed between the average CC for each participant and the distance from barbell to hip joint (−4.46), thigh length (−0.30), and mean velocity during the AP phase (−0.67), while a positive relationship existed with respect to shin length (3.98) and mean anterior-posterior displacement of the barbell (4.23). As the distance from the barbell to the hip joint decreases, the intra-individual consistency increases. The distance between the barbell and the hip joint is indicative of the trunk length. As a shorter trunk length is easier to stabilize, compared to a longer one, this could promote decreased movement variability. Similarly, a shorter thigh length would decrease both the knee and hip external moment arms during the squat, thereby decreasing the torque placed at each joint. In combination, a shorter trunk length and a shorter thigh length would result in less anterior lean of the trunk and more advantageous hip external moment arms, thus leading to less movement variability. As discussed previously, the timing related to the transition from descent to ascent during the SSC may have a profound impact on the squatting kinematics during the AP. This may in turn help explain why a lower mean velocity during the AP, results in less movement variability. The positive relationship between movement consistency and anterior-posterior displacement of the barbell and shin length could be the result of the high bar narrow stance squat style, applied by the participants. In this "weightlifting"-style squat, maximal forward knee travel is actively sought in an attempt to harness elastic recoil from the passive structures in the ankle and knee joints. In this way, the passive structures of the knee and ankle joints probably constrains the movement thereby facilitating less movement variability. Further, if the shin is longer, more forward knee travel is possible while maintaining the same angular displacement at the ankle joint. A key trait of the "weightlifting"-style squat, is also a very upright squatting position, which further indicates that having a short trunk and thigh, and a long shin in combination with greater anterior-posterior displacement of the barbell and slower velocities during the AP phase promotes movement consistency over movement variability.

It should be noted that in the analysis the timeline was normalized for each participant to 100 time points. This have removed some variability caused by the absolute time differences in the squat cycle time between participants and trials. However, as the primary aim of the study was to elaborate on the level of inter- and intra-individual variability in the kinematic (velocity) profiles (i.e. amplitude) of the back squat, this can effectively be performed using time normalization and application of the statistical parametric mapping procedure. The six lifting trials were performed at 90% of 1RM, and thus it is possible that fatigue may have influenced the performance of the participants. Fatigue has previously been shown to alter kinematics during the back squat (Trafimow, Schipplein, Novak, & Andersson, 1993). Therefore, some of the variability seen here may be caused by fatigue, however we did not observe any correlation between variability and trial number. Fatigue effects could have been avoided by performing the trials at a lower lifting load, but this would in turn have compromised the applicability of the results to performance at maximal lifting loads. The influence of fatigue was minimized by the long inter-set rest periods applied (i.e. 4–7 min), and this was further supported by a subsequent analysis showing no significant decline of peak barbell velocity throughout the trials. Lastly, as multiple comparisons are made in the present study, a correction for this could have been applied to guard against false-positive findings. However, as the main aim of the study was exploratory, and only a few planned comparisons were made, the need to correct for multiple comparisons were deemed redundant.

Considering the current results, where we have shown that trained participants perform the back squat exercise differently from one another, and with considerable variability from trial to trial, the notion that there is an "optimal" movement pattern for the back squat exercise, which should be adhered to by all individuals to attain maximum performance, is not supported. This finding has a major impact on the way the back squat exercise is being taught in a practical setting and the way that performance optimization in the exercise is carried out, as optimal movement is dependent on the individuals joint mobility, anthropometric characteristics, technical proficiency, skill level and muscular strengths and weaknesses. Thus, all these variables have to be taken into consideration when teaching or optimizing exercise technique in the back squat exercise, while acknowledging the fact that no individual is capable of producing invariant or identical movements. Collectively, this highlights the importance of analysing individual data when investigating the kinematics of the back squat in a performance optimization context.

In conclusion, the present study revealed significant inter- and intra-individual variability in the kinematics of the back squat in skilled weightlifters. This suggests that the back squat movement is variable between participants, and can be performed successfully using a variety of lifting strategies. Our results further indicated that having a short trunk and thigh, and a long shin in combination with greater anterior-posterior displacement of the barbell and slower velocities during the AP phase seems to promote intra-individual movement consistency over movement variability. Analysis of individual data from a given athlete should therefore be at the core of any attempt to optimize his or hers performance in the back squat exercise.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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