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Kinetic and Kinematic Changes during a 30-Repetition Bout of the Barbell Clean

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Abstract

The purpose of this investigation was to investigate the biomechanical effects of performing a large number of repetitions with a technically demanding exercise as is recommended in many extreme conditioning programs. Sixteen trained male participants (age: 24.1 ± 4.1 yr; stature: 180.1 ± 3.6 cm; mass: 94.6 ± 10.4 kg; resistance training experience: 6.0 ± 3.4 yr) performed 30 repetitions of the barbell clean in as short a duration as possible using the same absolute load of 62 kg. The participants also performed a baseline assessment comprising 6 repetitions with the same absolute load to provide a non-fatigued comparison. Discrete and continuous kinematic variables were quantified using 2D video analysis, whilst kinetics were quantified using force values collected from a force platform. Statistically significant differences in kinematic and kinetic values were observed between the baseline assessment and fatiguing protocol. However, the magnitude of these differences was classified as low to moderate. Knee flexion at the beginning of the movement was significantly lower during the 30 repetition protocol compared with baseline and decreased as fatigue accrued ($p<0.001$, eta squared=0.045). Accumulation of fatigue resulted in decreased hip flexion and increased ankle dorsiflexion at the catch phase ($p<0.001$, eta squared=0.040; $p=0.036$, eta squared =0.044, respectively). In contrast, continuous kinematic variables demonstrated that participants were able to maintain coordinated action between the hip and knee throughout the 30 repetitions. Collectively, the results demonstrate that despite relatively small changes to technique observed at the beginning and end of the barbell clean, the more important coordinative features of the movement can be maintained despite accruing substantial fatigue. It is recommended that if extreme conditioning programs are used with technically demanding resistance exercises then technique should be monitored and the session terminated if improper movement patterns emerge.

Keywords

Fatigue; Multi-joint; Vector coding; Variability

Introduction

Training programs characterized by the use of compound resistance exercises combined with high-volumes, moderate to high loads and short rest periods have become popular in both military and civilian populations [1,2]. Such programs are commonly referred to as extreme conditioning programs [1] and exercise professionals have predicted that participation in these activities will continue to increase in the near future [3]. However, a number of researchers have raised concerns regarding the safety of combing technically demanding ballistic resistance exercises with high-repetitions over short time periods [1,2]. In particular, it has been asserted that for ballistic exercises such as the barbell clean, fatigue accrued from performing high-repetitions can readily prompt unsafe movement execution and lead to acute injury [1]. There is however, limited data investigating potential biomechanical changes when performing technically demanding resistance exercises for high-repetitions, especially under the instruction to complete the set of repetitions as fast as possible as is frequently the objective set in many popular extreme conditioning programs [1,4].

Recently, Hooper et al. [2] performed a two dimensional biomechanical analysis of a fatiguing resistance training program comprising performance of the back squat, bench press and deadlift, each with 75% 1RM. The participants rotated around each exercise in a circuit, beginning with ten repetitions in a set and reducing the number performed consecutively by one until they reached the final set comprising a single repetition (i.e., fifty five repetitions were performed for each exercise). The participants were instructed to perform all prescribed repetitions as short a duration as possible with only those repetitions performed during the squat selected for biomechanical analysis. Technique was assessed by measuring the hip and knee angle at the bottom position of the squat. The authors reported changes in squat technique and suggested there was evidence of increased likelihood of injury as fatigue developed. In particular, the authors measured reduced movement at the knee joint (abbreviated squat depth) and determined that injury risk was increased due to greater forward lean of the trunk [2]. However, counter-intuitively, the results showed that squat depth increased and the amount of forward lean decreased across the repetitions as fatigue developed. The authors interpreted these results as evidence of participants adopting a self-preservation behavior at the beginning of the highly fatiguing task and that when they were confident in their ability to complete the protocol the participants adopted more appropriate and effective movement patterns [2].

The results from Hooper et al. [2] highlight the need for similar studies to include a baseline assessment of technique under non-fatiguing conditions. By incorporating a baseline assessment researchers can compare the kinematic values obtained with those measured at the very beginning of a fatiguing protocol and attribute any differences to behavioral changes rather than the development of fatigue. It is important to note that the protocol used by Hopper et al. [2] scaled the resistance used in each exercise relative to the participants 1RM. Whilst scaling of resistance is the most common and recommended practice for resistance training design, it fails to simulate a general feature of many extreme conditioning training programs where the same absolute load is used by a wide range of individuals and as a result, those that are stronger and better conditioned are able to complete the protocol in a shorter period of time [5]. In addition, the biomechanical assessment of technique conducted by Hooper et al. [2] relied solely on discrete variables

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including joint angles collected at a specific instant (e.g., the bottom position of the squat) and as a result fails to capture information relevant to describing the overall movement pattern and its variability over time [6]. More effective biomechanical assessments of technique may be obtained by combining traditional discrete measures with contemporary analysis methods that focus on the coordination of multiple segments [7]. Therefore, it was the purpose of this study to incorporate both discrete and continuous analysis methods to compare the technique of a complex resistance training movement performed under a traditional framework of minimal fatigue with a protocol that featured a high number of repetitions and generated substantial fatigue. The barbell clean was selected for this study as it represents a class of exercise most often cited as unsuited for such training programs and despite these recommendations is still commonly used in increasingly popular extreme conditioning programs [1,8]. It was hypothesized that fatigue would significantly alter lifting technique and also interrupt coordination between segments.

Methods

Participants

Sixteen trained males (age: 24.1 ± 4.1 yr; stature: 180.1 ± 3.6 cm; mass: 94.6 ± 10.4 kg; self-reported barbell clean 1RM: 111.5 ± 12.0 kg; resistance training experience: 6.0 ± 3.4 yr) participated in this study. Participants were recruited from gymnasiums that resided in a 60 mile radius from the University facilities and specialized in extreme conditioning programs characterized by the use of compound resistance exercises combined with high-volumes, moderate to high loads and short rest periods (in the capture area 6 gymnasiums matching this criteria were identified). All participants recruited had a minimum of three years experience performing the barbell clean, were accustomed to performing the movement across a high number of repetitions and were able to complete the prescribed number of repetitions set out in the protocol. Participants were notified about the potential risks involved and provided their written informed consent to be included. Prior approval for the study was obtained from the ethical review panel at the Robert Gordon University, Aberdeen, UK.

Testing protocol

The fatiguing protocol for the study required each participant to perform thirty repetitions of the barbell clean with a 62 kg load in as short a time as possible. The load and exercise were selected based on a modified form of a popular workout used in extreme conditioning programs [5]. The majority of participants performed the power clean version of the movement for the entire protocol. However, participants were instructed simply to clean the barbell to the shoulder position and only a small number of participants descended into a full squat to complete the final repetitions of the protocol. To provide a baseline assessment of technique and kinetic output, each participant performed six repetitions of the barbell clean with the same absolute load (62 kg). An inter-repetition rest period of ten seconds and the instruction to perform the movement as explosively as possible was given. The baseline protocol was performed first to avoid fatigue confounding results. A ten minute recovery period was provided between the baseline and fatiguing protocol.

Biomechanical instrumentation

The repetitions were videoed at 100 Hz (GigE, UI-5220RE) and digitized using video analysis software (Quintic Biomechanics v21; Quintic Consultancy Ltd, Coventry, UK). Markers with contrasting colours were positioned in the sagittal plane at the end of the barbell and on the right hand side of the body down the midline of the trunk, hip joint centre, lateral femoral condyle, lateral malleolus and at the approximate location of the metatarsal-phalangeal joint of the fifth metatarsal. Markers were placed only on one side of the body and bilateral symmetry was assumed. The optical axis of the video camera was aligned to the centre of the hip and setup to maximize the lifter-barbell system and increase the accuracy of digitization. Each video file was calibrated using a 1.5×1.5 m calibration frame to translate position and distances into an accurate orthogonal XY Cartesian space. The start and end of each repetition were visually identified as the frame prior to vertical liftoff and the frame where the barbell contacted the shoulder in the catch position, respectively. All repetitions were performed on a single force platform (Accupower, AMTI, Watertown, Massachusetts, USA) with dimensions 76×102×12 cm (length×width×height) using a recording frequency of 500 Hz to calculate external kinetics.

Data reduction

Discrete kinematic variables included joint angles (hip, knee and ankle) measured at the beginning and end of each repetition. Joint angles were defined so that in the anatomical position the hip, knee and ankle values measured 0°, 0° and 90°, respectively. Angles greater than 90° measured at the ankle corresponded to plantar flexion. In addition, motion of the barbell was described by measuring total vertical displacement, horizontal displacement from the start position to the catch position, and the horizontal displacement from the most forward position to the catch position [9]. Velocity of the barbell was calculated by taking the first derivative of the position data using a Lagrangian five point differentiation scheme [10]. Continuous analysis of the kinematic data was based upon quantitative description of the angle-angle diagram for the hip and knee. An angle-angle diagram represents a plot of one angle as a function of another angle. In the present study the hip angle at each instant in time was plotted on the x-axis and the corresponding knee angle was plotted on the y-axis. The resulting shape that the plot makes provides insight into the coordination of the adjacent joints. In order to extract quantitative information regarding shape and variability of the hip and knee angle trajectories a vector coding technique which breaks the plot into small vectors was used. The relative motion of the hip and knee were selected for analysis due to the proximal to distal sequencing that occurs in ballistic motions such as the barbell clean and the importance of knee joint motion which has been highlighted previously [11,12]. Vector coding was performed using the method developed by Tepavac and Field-Fote [13]. Firstly, hip and knee angles across each repetition were interpolated to 101 data points using a cubic spline procedure. Data were then plotted on an angle-angle diagram with the x-axis representing the hip angle and the y -axis representing the knee angle. Between each pair of consecutive data points a vector was calculated to represent the relative motion of the hip and knee over the time course of the repetition. The length of the vector was calculated as $l_{n,n+1} = \sqrt{(x_{n,n+1})^2 + (y_{n,n+1})^2}$ where $x_{n,n+1}$ is the difference in hip angle value between frame n and frame n+1 and $y_{n,n+1}$ is the difference in knee angle value between frame n and frame n+1. The cosine and sine of the angle created by the vector and the right hand x-axis were found using the formulas: $\cos\theta_{n,n+1} = x_{n,n+1} / l_{n,n+1}$ and $\sin\theta_{n,n+1} = y_{n,n+1} / l_{n,n+1}$. The angle θ is referred to as the coupling angle (0-360°) and quantifies the relative motion of the hip and knee. Between each frame the coupling angle was calculated and assigned to a category to identify the portion of the movement as: 1. Hip dominant phase (0< θ ≤ 22.5°, 337.5 < θ ≤ 360°); 2. In-phase (hip and knee extending/flexing together, 22.5 < θ ≤ 67.5°, 202.5 < θ ≤ 247.5°); 3. Knee dominant phase (67.5 < θ ≤ 112.5°, 247.5 < θ ≤ 292.5°); 4. Anti-phase (one joint extending whilst the other is flexing, 112.5 < θ ≤ 157.5°, 292.5 < θ ≤ 337.5°) [14] (Figure 1).

To analyse variability in the coordinated actions of the hip and knee, repetitions were sectioned into blocks of six. The first block comprised the baseline protocol (BASE), the second block comprised the first six repetitions of the fatiguing protocol (F1-6), the third block comprised the thirteenth to eighteenth repetitions of the fatiguing protocol (F13-18), and the fourth block comprised the final six repetitions of the fatiguing protocol (F25-30). Using the vector coding method developed by Tepavac and Field-Fote [13], variability in the coordinated actions of the hip and knee were assessed according to the shape of the angle-angle plots (parameter $\overline{a}$), the magnitude of the individual vectors that produced the plots (parameter $\overline{m}$), and a final parameter that combined both sets of information (parameter $\overline{r}$). To assess variability in shape, a mean coupling angle for each frame-to-frame interval was obtained across the six repetitions in each block using the formula $a_{n,n+1} = \sqrt{(\overline{\cos\theta})^2 + (\overline{\sin\theta})^2}$ where $(\overline{\cos\theta})$ and $(\overline{\sin\theta})$ are the mean cosine and sine of the coupling angle between frame *n* and frame n+1 across six repetitions, respectively. The final shape parameter $\overline{a}$ was calculated by taking the average of $a_{n,n+1}$ across the 100 frame-to-frame intervals and ranged between 0 and 1. To assess variability in magnitude, the vector lengths between frames were normalized across the six repetitions by dividing each vector by the maximum length measured within the specific frame-to-frame reference: $l'_{n,n+1}[i] = \frac{l_{n,n+}[i]}{\max(\text{ln,n+1[i]})}, i = 1,2,....,6.$ The standard deviation of the normalized lengths across the six repetition for each fame-to-frame interval was then calculated. The standard deviations were then also normalized to provide a measure of variability for each frame-to-frame interval that was forced to take a value between 0 and 1: $m_{n,n+1} = \frac{\sigma(l'_{n,n+1})}{\sigma_{\max}}$ where $\sigma(l'_{n,n+1})$ is the standard deviation of the normalized lengths across the six repetitions between frame *n* and frame n+1 and $\sigma_{\max}$ is the maximum value that the standard deviation could take. The final magnitude parameter $\overline{m}$ was calculated by taking the average of $m_{n,n+1}$ across each of the frame-to-frame intervals and ranged between 0 and 1. Finally, the combined shape and magnitude parameter $\overline{r}$ was calculated by taking the average of the product $a_{n,n+1} \times m_{n,n+1}$ across each of the frame-to-frame intervals, with the value also ranging between 0 and 1.

Data collected from the force platform were used to calculate peak force and rate of force development (RFD). These kinetic variables were measured primarily to identify fatigue during the 30 repetition protocol and also to identify if pacing strategies were adopted. Peak force was defined as the largest vertical ground reaction force (VGRF) measured during the propulsive phase of the movement. RFD was measured by calculating the gradient of the VGRF-time curve which monotonically led to the peak value. The initial point of the slope was defined as the first VGRF value in the longest monotonic sequence culminating in the peak value identified. The slope of the gradient was obtained using the formula $\frac{F_{\max} - F_{initial}}{\Delta t}$ where $F_{\max}$ is the peak VGRF value measured, $F_{initial}$ is the VGRF value measured at the initial point of the slope, and Δt is the time elapsed between the two force values. Peak force and RFD were calculated for each repetition and then averaged across the six repetition blocks previously identified.

Statistical analysis

All variables calculated were averaged across the six repetitions of their respective block (BASE, F1-6, F13-18, F25-30). In order to assess reliability of the digitisation process, six of the thirty repetition trials were digitised twice by two of the researchers. Inter- and intra-observer reliability were quantified for repeated measures of the X and Y coordinate values across markers using the Bland and Altman [15] method. Inter- and intra-observer mean differences ranged from -0.04 cm to 1.41 cm, demonstrating high reliability. Data for each of the variables collected were assumed to be normally distributed based on the results of Shapiro-Wilks tests. Potential differences between blocks were analysed using a one-way repeated measures ANOVA. Bonferroni adjustment was performed given a significant *F* statistic ($p<0.05$) to obtain post hoc pairwise tests. For all significant pariwise comparisons the standardized mean difference (d_{RM}) was calculated by dividing the difference in means by the standard deviation of difference scores [16]. For reporting purposes the range of (d_{RM}) values for the significant pairwise comparisons were provided. An Effect size for each omnibus ANOVA was calculated using the eta squared statistic $\eta^2 = \frac{SS_{effect}}{SS_{total}}$ with η^2 values of 0.02, 0.13 and 0.26 used to indicate a small, medium and large effect, respectively [17]. All statistical tests were performed with SPSS software (SPSS, Version 21, SPSS Inc., Chicago, IL).

Results

Moderate between participant variation was observed in the self-reported 1RM's (111.5 ± 12.0 kg) with the coefficient of variation (SD/mean) equal to 0.11 and a large overall range extending from 85 to 150 kg. Greater between participant variation was observed in the time taken to complete the thirty repetitions (201 ± 129s) with the coefficient of variation equal to 0.64 and the overall range extending from 62 to 520 s. Analysis of the kinetic data demonstrated a reduction in peak force and RFD as the number of repetitions completed in the fatiguing protocol increased. Figure 2, reveals that peak force at the start of F1-6 was similar in magnitude to peak force produced during BASE. However, a relatively consistent decrease in peak force was observed across the thirty repetitions. Table 1, provides a comparison of peak force and RFD values averaged across the different blocks, with significant effects obtained for both variables [$F(1.7,25.3)=16.287$, $p<0.001$, d_{RM} =0.76-1.55; $F(3,45)=8.414$, $p<0.001$, d_{RM} =0.88-0.94; respectively].

Analysis of the discrete kinematic data identified significant differences in joint angles adopted at the start and end of the barbell clean (Table 2). Greater knee flexion at the beginning of the movement was measured during the BASE protocol compared with all sections of the fatiguing protocol [$F(3,51)=9.912$, $p<0.001$, d_{RM} =0.61-1.42]. No significant differences were observed for hip or ankle angles adopted at the start of the movement [$F(2.2,36.9)=0.613$, $p=0.560$, $F(3,51)=2.610$, $p=0.061$, respectively]. Conversely, significant main effects were obtained for hip and ankle angles at the end of the barbell clean [$F(3,51)=9.714$, $p<0.001$, d_{RM} =0.61-1.15; $F(1.6,27.7)=4.072$, $p=0.035$, d_{RM} =0.62-0.68; respectively]. Post hoc tests revealed that the hip was significantly more flexed, and the ankle was significantly less dorsiflexed at the end of the barbell clean during BASE and F1-6 in comparison with F13-18 and F25-30.

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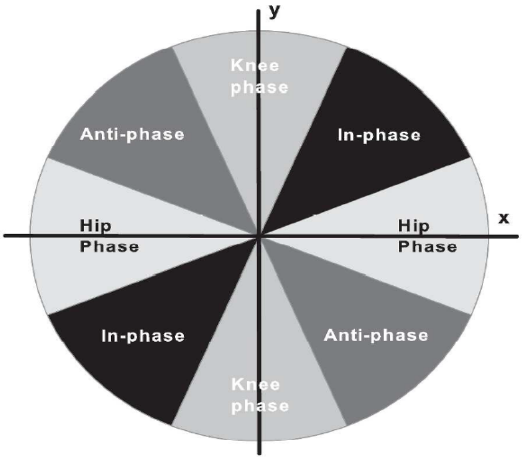

Figure 1: Categorization of relative hip and knee motion based on measurement of coupling angle.

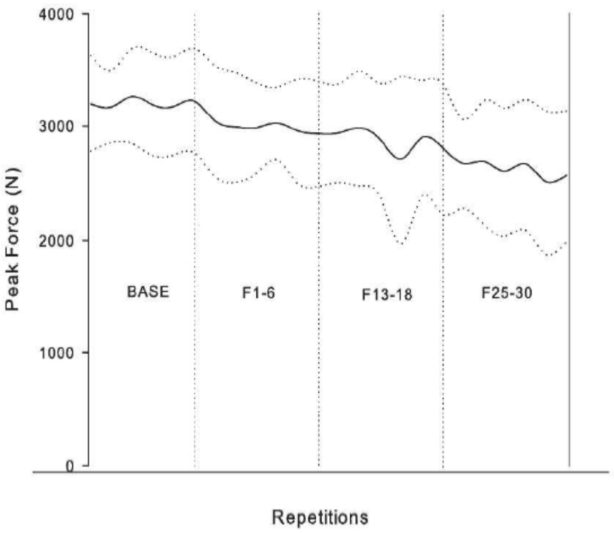

Figure 2: Interpolated plot of peak force values measured for all repetitions performed during the BASE and fatiguing protocol.

The solid line represents peak force data averaged across participants for the six repetitions of the BASE protocol and the thirty repetitions of the protocol. Broken lines represent the standard deviation computed across participants.

Analysis of coupling angles, which were used to describe the relative motion of the hip and knee, demonstrated no significant differences in the distribution of phases across the repetition blocks [in-phase: $F(3,45)=2.512$, $p=0.071$; hip dominant phase: $F(3,45)=1.616$, $p=0.199$; knee dominant phase: $F(3,45)=2.391$, $p=0.081$; anti-phase: $F(1.9,28.7)=2.814$, $p=0.079$; (Figure 3). The consistency in relative motion between the hip and knee across the different blocks is illustrated in more detail in the angle-angle diagram of Figure 4.

Results describing the variability of the relative motion between the hip and knee (measured within each block of repetitions) showed no significant differences in movement variation with regards to shape, magnitude or the combination of shape and magnitude across the repetition blocks [$\bar{a}$: $F(3,45)=0.700$, $p=0.557$; $\bar{m}$: $F(3,45)=1.065$, $p=0.373$; $\bar{r}$: $F(3,45)=0.977$, $p=0.412$, respectively].

Analysis of barbell positional data demonstrated that there were no significant differences across repetition blocks for either vertical displacement [$F(3,45)=2.043$, $p=0.121$] or horizontal displacement [start to catch: $F(3,45)=1.453$, $p=0.240$; forward to catch: $F(3,45)=1.197$, $p=0.322$, Table 4]. In contrast, peak velocity was greatest during the BASE protocol and progressively decreased across repetitions performed in the fatiguing protocol [$F(3,45)=4.085$, $p=0.012$, $d_{RM}=0.64$].

Discussion

The results of the present study support the initial component of the hypothesis and demonstrate that protocols typical of that used in extreme conditioning programs involving high-repetitions performed in as short a duration as possible have the potential to cause statistically significant changes in kinematics and kinetics associated with complex resistance exercises such as the barbell clean. It appears that the kinematic changes observed occur as a result of the fatigue developed and the task constraint of attempting to complete the prescribed number of repetitions in a minimum amount of time. However, it is important to note that the changes in kinematics observed were relatively small in magnitude compared with variation across individuals performing the same movement. That is, effect sizes for all significant kinematic differences were small to moderate. In contrast, no evidence was found to support the latter component of the research hypothesis and analysis of angle-angle trajectories illustrated that the participants were able to maintain the important feature of coordinating the action of the hip and knee despite the fatigue elicited.

The decision to use the same absolute load for all participants had a large effect on the performance outcome of the fatiguing protocol. Overall, there was moderate between participant variation in the maximum strength of the participants; however, there was a large range in the self-reported 1RM's (85 - 150 kg) and this led to the time to complete the protocol ranging extensively from 62 seconds (strongest athlete) to 520 seconds (weakest athlete). In many extreme conditioning programs that combine technical resistance exercises and highly fatiguing routines there is the potential to scale the program to an athlete's ability by manipulating the exercise, load or other relevant factors [18]. However, in many cases there will exist a large range in strength between athletes using the same resistance and the results from this study highlight a potential difficulty in training prescription of a system that frequently uses absolute loads.

The kinetic data collected in the present study established that fatigue was elicited during performance of the thirty repetitions, with gradual decreases identified in both peak force and RFD (Table 1 and Figure 2). It is important to note that the BASE protocol was implemented to provide a comparison to determine if changes in variables were influenced by fatigue or by the task constraint of attempting to complete the prescribed number of repetitions in as short a duration as possible. Both peak force and RDF values measured during the first six repetitions of the fatiguing protocol were lower than that measured during BASE; however, differences were not significant. Peak force values continued to decrease across F13-18 and F25-30 with significantly lower values obtained between F25-30 and all other repetition blocks. RFD values also decreased across F13-18 and F25-30 with significant differences only noted between BASE and the final two repetition blocks of the fatiguing protocol. These results suggest that kinetic data may have been

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Table 1: (mean ± SD) Comparison of kinetic variables.

	BASE	F1-6	F13-18	F25-30	*p*	η^2
Peak GRF (N)	3191 ± 402#†	2968 ± 388†	2827 ± 513†	2583 ± 527	0.000	0.220
RFD (Ns^{-1})	9803 ± 4082#†	8635 ± 4093	7679 ± 4056	7073 ± 3869	0.000	0.074

#Significantly greater than F13-18 (p<0.05), †Significantly greater than F25-30 (p<0.05). BASE=baseline assessment, non-fatiguing 6 repetitions. F1-6=repetitions 1 to 6 of fatiguing protocol. F13-18=repetitions 13 to 18 of fatiguing protocol. F25-30=repetitions 25 to 30 of fatiguing protocol.

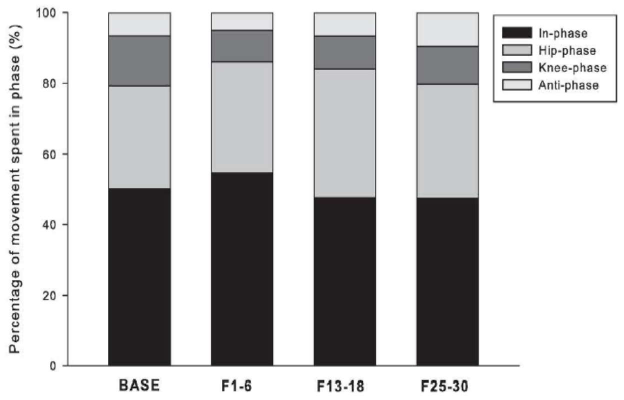

Figure 3: Distribution of coupling angles into relative motion phases.

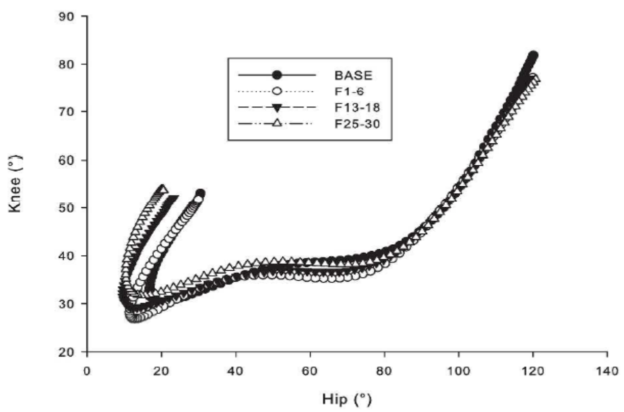

Figure 4: Angle-angle diagram displaying the relative hip and knee motion averaged across participants.

influenced to some extent by the task constraint, however, fatigue appeared to be more influential, as evidenced by the progressive decline in output across repetitions. Perhaps surprisingly, the effect size calculated for the overall difference in peak force measured across all repetitions was categorized between small and medium, and for RFD was categorised as small. These results should not be interpreted as signifying the performance of high numbers of repetitions have only limited effect on kinetic output. Previous research by Cormie et al. [19] has demonstrated that for the power clean kinetic variables are maximized when using maximum or near maximum loads. For the majority of participants in the present study, the load used was substantially below their 1RM. Therefore, it is clear that the kinetic profile developed during a protocol similar to the one implemented here would be markedly different from that attained in a traditional framework using near maximum loads.

Further analysis of the kinematic data revealed a number of differences between the BASE and the fatiguing protocol that suggests the effects were caused by both the task constraint and fatigue. Knee angles adopted at the very beginning of the movement showed significantly less flexion during BASE compared with F1-6, highlighting differences were most likely caused by the task constraint as fatigue at this stage would be minimal (Table 2). In addition, the results show that as repetitions progressed and fatigue began to accumulate, the amount of knee flexion at the start of the movement continued to decrease. Previous research conducted by Hooper et al. [2,20] correspond with the results obtained here and demonstrate that fatigue caused by maximum contractions and task constraints have the potential to affect knee kinematics. In the authors first study [20], it was reported that knee flexion at the beginning of a bodyweight squat decreased after performing a fatiguing workout (pre workout: 118° *vs.* post workout 105°). The authors suggested that the altered movement pattern occurred in response to fatigue as a means of reducing the amount of work required and therefore the energy demand [20]. In the authors follow up study [2], participants performed the same fatiguing workout whilst kinematic variables were collected during performance of a loaded squat (75% 1RM). In contrast to the results obtained here and in the authors' previous study [20], Hooper et al. [2] reported that the amount of knee flexion increased as the protocol and fatigue progressed. The authors hypothesised that these divergent results were due to the task constraints and a self-preserving behavior adopted by the participants. The fatiguing protocol used by Hooper et al. [2] progressively decreased the number of repetitions performed in each circuit. During the initial circuits where the repetitions were high participants may have adopted less knee flexion at the bottom of the movement to ensure that the set could be completed. In contrast, towards the end of the program when the number of repetitions to be performed were lower, the participants would have to adopt less of an anticipatory behavior [21] and could produce the knee angle they would normally use when squatting.

In contrast to the squat exercise where it is customary to consider a minimum knee angle to represent a successful lift, a range of knee angles can be adopted at the initial concentric phase of the barbell clean. Compared to movements such as conventional deadlifts and sumo deadlifts, research has established that elite athletes begin the barbell clean with a more flexed knee position (~ 125°,137° and 100°, respectively) [11,22]. This configuration is adopted as it enables the lifter to effectively utilize the DKB technique and to maximize force production during the second pull [12]. However, starting in a deep squat position creates additional work and is likely to increase repetition duration due to the additional time required to adopt the position and the greater range of motion traversed. During the fatiguing protocol in the present study where the load was submaximal and the task constraint was to complete the repetitions in as short duration as possible, it appears reasonable that the participants would reduce the amount of knee flexion. In addition, as fatigue increased participants may have continued to decrease their knee angle at the start of the movement to reduce the initial mechanical load.

The results obtained in the present study also identified significant differences for joint angles adopted at the end of the movement,

Table 2: (mean ± SD) Comparison of joint angles defined as the start of the movement (initiation of 1st pull) and end of the movement (initiation of catch phase).

	BASE	F1-6	F13-18	F25-30	*p*	η^2
Initial hip angle (°)	120.6 ± 8.7	120.2 ± 8.8	119.2 ± 7.6	120.5 ± 7.9	0.560	0.004
Initial knee angle (°)	83.2 ± 12.1*#†	77.0 ± 12.4†	76.3 ± 11.6	72.9 ± 9.3	0.000	0.044
Initial ankle angle (°)	95.1 ± 6.4	98.1 ± 6.4	97.2 ± 4.8	96.7 ± 6.8	0.061	0.035
Final hip angle (°)	30.7 ± 18.0#†	29.9 ± 19.8#†	23.0 ± 17.8	20.5 ± 17.6	0.000	0.043
Final knee angle (°)	52.1 ±16.4	51.8 ± 18.6	52.2 ± 16.4	53.6 ± 15.1	0.937	0.002
Final ankle angle (°)	92.4 ± 7.1#†	92.2 ± 6.6#†	87.1 ± 5.2	85.4 ± 5.1	0.035	0.051

*Significantly greater than F1-6 (p<0.05), #Significantly greater than F13-18 (p<0.05), †Significantly greater than F25-30 (p<0.05). BASE=baseline assessment, non fatiguing 6 repetitions. F1-6=repetitions 1 to 6 of fatiguing protocol. F13-18=repetitions 13 to 18 of fatiguing protocol. F25-30=repetitions 25 to 30 of fatiguing protocol.

Table 3: (mean ± SD) Comparison of within repetition block movement variability.

	BASE	F1-6	F13-18	F25-30	*p*	η^2
Shape parameter ($\bar{\alpha}$)	0.87 ± 0.07	0.87 ± 0.07	0.88 ± 0.07	0.88 ± 0.06	0.557	0.026
Magnitude parameter ($\bar{m}$)	0.60 ± 0.04	0.62 ± 0.06	0.61 ± 0.03	0.62 ± 0.06	0.373	0.047
Combined parameter ($\bar{r}$)	0.54 ± 0.08	0.55 ± 0.08	0.55 ± 0.05	0.56 ± 0.09	0.977	0.040

BASE=baseline assessment, non fatiguing 6 repetitions. F1-6=repetitions 1 to 6 of fatiguing protocol. F13-18=repetitions 13 to 18 of fatiguing protocol. F25-30=repetitions 25 to 30 of fatiguing protocol.

Table 4: (mean ± SD) Comparison of barbell kinematic variables.

	BASE	F1-6	F13-18	F25-30	*p*	η^2
Vertical height (m)	1.22 ± 0.15	1.20 ± 0.18	1.18 ± 0.17	1.20 ± 0.13	0.121	0.003
Peak velocity (ms^{-1})	2.46 ± 0.34†	2.39 ± 0.41	2.33 ± 0.39	2.20 ± 0.33	0.012	0.043
Start to catch (cm)	8.6 ± 3.2	6.3 ± 6.4	6.3 ± 6.6	7.3 ± 5.9	0.240	0.028
Forward to catch (cm)	11.9 ± 3.0	9.7 ± 4.5	10.3 ± 4.7	11.4 ± 3.9	0.322	0.041

†Significantly greater than F25-30 (p<0.05). BASE=baseline assessment, non-fatiguing 6 repetitions. F1-6=repetitions 1 to 6 of fatiguing protocol. F13-18=repetitions 13 to 18 of fatiguing protocol. F25-30=repetitions 25 to 30 of fatiguing protocol.

which was defined as the point when the barbell contacted the shoulders (i.e. during the catch phase). No differences in joint angles were obtained between BASE and F1-6, indicating that effects were most likely caused by fatigue. The results showed that as the number of repetitions increased, the hip exhibited less flexion and the ankle exhibited greater dorsiflexion. Generally when the clean is performed and the athlete propels the barbell upward, they flex at the lower body joints to lower the Centre of Mass (COM) so that the barbell can be caught on the shoulders at a reduced height. As repetitions increased and the athletes became more fatigued, it is possible that they adopted the strategy to lower the COM through less hip flexion and more ankle dorsiflexion to reduce energy demand required to rise from a squat with the hips in a more extended position [23]. This altered lifting strategy is likely to reduce the effectiveness of the exercise.

Restricting biomechanical analyses to discrete kinematic data has the potential to overlook important information, particularly information relevant to describing coordination of body segments and their variability [6]. To analyse the relative motion of the hip and knee, a vector coding method that quantified various features of the angle-angle plot of the two joints was used [13]. The coupling angle calculated in the present study identified whether sections were dominated by movement at one joint, or whether the motion featured a more coordinated action of the joints either in-phase or anti-phase. The results demonstrated that across all repetition blocks the joints primarily exhibited in-phase coordinated motion, with the next most common action comprising hip dominated movement, then knee dominant movement, and finally anti-phase movement (Figure 3). No significant differences were noted in the percentage of movement comprised by any of the phases, suggesting that the relative motion of the hip and knee for the participants as a whole were not influenced by the task constraint or the accumulation of fatigue (Figure 4).

Variability within each repetition block was also assessed using the vector coding method. This was achieved by quantifying the variability in shape, magnitude and overall profile of the angle-angle diagrams representing the coordinated action of the hip and knee. Traditionally, movement variability has been viewed as noise within data and a source of error that should be removed using various filtering techniques [24]. More recently, biomechanists have proposed that movement variability is an essential feature of the sensory motor system that enables individuals to adapt to dynamic environments and may also be important in injury prevention [24]. In relatively fixed environments such as those encountered during resistance training where repetitive actions are completed, movement variability may facilitate more effective distribution of loads throughout tissues and provide a protective mechanism [25]. Edwards et al. [26] quantified variability at the ankle and knee during an explosive lower-body exercise before and after a fatiguing protocol. The authors quantified variability through a coefficient of variation statistic calculated at discrete points during the movement. The participants included well trained athletes that demonstrated greater movement variability when fatigued whilst maintaining similar kinematics to that measured in their non-fatigued state. In some instances the coefficient of variation increased from 10.9% in the non-fatigued state to 76.2% in the fatigued state. The authors hypothesized that in the group of well-trained athletes the increased movement variability acted as a protective mechanism to mitigate the negative effects of fatigue by more effectively distributing mechanical stress from the activity. In the present study no significant differences in any of the variability parameters for the coordinated action of the hip and knee were found (Table 3). Further research is required to clarify the role of movement variability on injury likelihood and to understand the effect of fatigue, especially during resistance exercise where extremely large forces can be transmitted within the body. As reported by Cortes et al. [25] variable selection can influence the relationship between fatigue and movement variability. In the present study only one variable was selected for analysis of variability in the time domain, and it is possible that other kinematic variables including the movement of joints in other planes may have provided different results.

As a final means of investigating the biomechanical effects of a fatiguing protocol on a technically demanding resistance exercise, kinematics of the barbell were measured. Previous research has demonstrated that fatigue has the potential to influence lifting technique and subsequently the path of the barbell. Haff et al. [27] investigated the effects of including inter-repetition rest periods during the clean pull on peak barbell velocity and displacement. The study featured experienced athletes that performed one set of five repetitions using 90 and 120% of their power clean 1RM either in a continuous fashion or with 10-30 seconds rest between repetitions. Similar to the results obtained in the present study, Haff et al. [27] reported that significantly greater peak velocity values were obtained during the protocol with inter-repetition rest. However, in contrast to the results obtained in the present study, Haff et al. [27] reported that the accumulation of fatigue reduced the vertical displacement of the barbell. The contrasting results obtained is most likely due to the different loads used. In the present study, the absolute load lifted by the participants represented between 40 and 67% of the individuals self reported barbell clean 1RM. In contrast, the loads lifted in the study conducted by Haff et al. [27] included 90 and 120% 1RM and significant differences in vertical displacement were only obtained with the heavier resistance.

Similar load dependent effects may have influenced findings for the horizontal displacement of the barbell. Hardee et al. [28] recorded differences in horizontal displacement when ten recreationally trained weightlifters performed the power clean for three sets of six repetitions with 80% 1RM and either no rest, twenty seconds rest, or forty seconds rest between repetitions. The authors [3] found that with no rest and the accumulation of greater fatigue, horizontal displacement of the barbell decreased, whereas, with forty seconds rest between repetition (and reduced fatigue) the amount of horizontal displacement either increased or any decreases were attenuated. In the present study the largest horizontal displacements were obtained during the BASE protocol, however, differences between repetitions performed during the fatiguing protocol were not significant (Table 4).

Several limitations of the present study exist. The kinematic analysis was based on movement in only two dimensions and therefore cannot determine if fatigue or the task constraint affected kinematics or kinetics of the lower body joints in the frontal or transverse planes. The majority of biomechanical research on the barbell clean has focused on sagittal kinematics and kinetics, however, previous research conducted on the squat exercise has demonstrated that substantial hip movement can occur in both the frontal and transverse planes Swinton et al. [29] and therefore may also occur during the barbell clean. Further research is required to better understand the three dimensional kinematics and kinetics of the lower body during the barbell clean and assess if fatigue may impair technique or the forces experienced. A second limitation of the study is that the biomechanical analysis focused on the pulling phase and provides minimal information regarding the receiving and catch phase where high eccentric loads may have the potential to cause injury. A third and related limitation of the study is the inability to link directly any of the biomechanical variables measured to injury risk. Finally, due to the relatively large range in strength of the participants and use of the same absolute load the amount of fatigue elicited would have been variable and therefore the effects of fatigue would be variable also, thus reducing the power of the analyses. However, the purpose of the present study was to better understand the effects on technique when performing a complex resistance exercise such as the barbell clean under fatiguing protocols now commonly performed by many recreational trainers and athletes in extreme conditioning programs. Future research should include biomechanical variables such as loading rate and internal kinetics to provide information regarding the potential injury risk. In addition, future research may choose to scale loads and/or monitor fatigue to ensure that similar levels of fatigue are obtained across the participants.

Perspectives

The results of the present study demonstrate that experienced athletes can perform a high number of repetitions consistent with that used in many contemporary extreme conditioning programs with a technically demanding resistance exercise and maintain the most salient features of the movement. It is important to note that the participants in the present study had an average resistance training experience of over five years and a minimum experience of three years performing the power clean. Similar results and the ability to maintain technique under substantial states of fatigue may not be typical of less experienced athletes. The results obtained here suggest that this type of training should be supervised and athletes may need to be educated to monitor their technique and include rest periods or terminate any sets if substantial changes in their movement pattern are identified. Further research is required to investigate a wider variety of fatiguing protocols used with resistance exercises and ascertain which strategies provide the greatest adaptations whilst minimizing injury risk.

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