Differences in muscle synergies between skilled and unskilled athletes in power clean exercise at various loads

Hakariya, Nadaka
Kibushi, Benio
Okada, Junichi

(Citation)
Journal of Sports Sciences,41(11):1136-1145

(Issue Date)
2023-06-03

(Resource Type)
journal article

(Version)
Version of Record

Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjsp20

Differences in muscle synergies between skilled and unskilled athletes in power clean exercise at various loads

Nadaka Hakariya, Benio Kibushi & Junichi Okada

To cite this article: Nadaka Hakariya, Benio Kibushi & Junichi Okada (2023) Differences in muscle synergies between skilled and unskilled athletes in power clean exercise at various loads, Journal of Sports Sciences, 41:11, 1136-1145, DOI: 10.1080/02640414.2023.2259268

To link to this article: https://doi.org/10.1080/02640414.2023.2259268

Published online: 20 Oct 2023.

JOURNAL OF SPORTS SCIENCES
2023, VOL. 41, NO. 11, 1136–1145
https://doi.org/10.1080/02640414.2023.2259268

SPORTS MEDICINE AND BIOMECHANICS

OPEN ACCESS Check for updates

Differences in muscle synergies between skilled and unskilled athletes in power clean exercise at various loads

Nadaka Hakariya[a], Benio Kibushi[b] and Junichi Okada[c]

[a]Graduate School of Sport Sciences, Waseda University, Saitama, Japan; [b]Graduate School of Human Development and Environment, Kobe University, Kobe, Japan; [c]Faculty of Sport Sciences, Waseda University, Saitama, Japan

ABSTRACT

The purpose of this study was to determine the differences in muscle synergy between skilled and unskilled participants using various loading conditions for power clean. Nineteen participants (ten skilled and nine unskilled) performed power clean at 60–90% one repetition maximum (1RM), while measured 12 muscles across the entire body. The vertical impulse was calculated for the unweighting associated with the double-knee bend (DKB) manoeuvre in power clean. Muscle synergies were extracted using non-negative matrix factorization. The weighting of muscle synergies was subsequently compared between the two groups for all loads, and confidence intervals were calculated. The number of muscle synergies in both groups was three, and the functions of all muscle synergies were similar. Muscle synergy 1 involved the first pull, muscle synergy 2 involved the transition and the second pull, and muscle synergy 3 involved DKB. No significant difference in either muscle synergy was observed at 60–80% 1RM weight, while the 90% 1RM showed significantly active in the ankle plantar flexor and knee extensor muscles for muscle synergy 3, which involved DKB only in the skilled group. This indicates that increased joint stiffness during DKB may minimize unweighting. Unskilled individuals may acquire such muscle synergies to lift greater weights.

ARTICLE HISTORY
Received 5 April 2023
Accepted 5 August 2023

KEYWORDS
Weightlifting; power clean; muscle synergy; double knee bend; resistance training

Introduction

Many athletes, including weightlifters, have adopted Olympic lifting to improve athletic performance (i.e., jumping, sprinting) (Hackett et al., 2016). The most familiar exercise is the power clean, which requires explosive power and whole-body coordination. Although it is widely used in the sports to learn proper muscle coordination (United States Weightlifting Association, 2015), few studies thus far have quantitatively analysed muscle coordination in weightlifting. Quantification of muscle coordination in skilled individuals may assist coaches in improving the performance of novices and unskilled Olympic lifters.

In weightlifting, the pulling motion of the barbell is generally divided into three phases: first pull, transition, and second pull. It is well established that skilled lifters executed characteristic movements, such as double-knee bend (DKB), in the transition phase and triple extensions in the second pull phase (Enoka, 1979; Stone et al., 2006). This suggests that learning proper DKB and triple extension are necessary for novices and unskilled to lift greater weights. It is thought that DKB reduces the moment arm of the barbell, back, and hip extensors (Enoka, 1979). The barbell must be help proximally to lift it upward, while transferring as much as possible of the exerted power. Since the hip and back extensor muscle groups are large and capable of exerting greater power, holding the barbell proximally during DKB is thought to be an advantageous strategy for lifting. Furthermore, the knee joint exhibits an extension-flexion-extension during DKB, which likely utilizes the stretch-shortening cycle (SSC) (Enoka, 1988). In addition, it has been reported that experienced weightlifters have greater ankle plantar flexion torque in triple extension and increased ground reaction force after DKB compared with novices (Kibushi et al., 2020; Nagao et al., 2016). Haug et al. (2015) reported that, after a certain period of practice on power clean, novices showed improvements in DKB and triple extension movements and increased the power exerted during the power clean. These findings suggest that there may be improvements in DKB, and triple extension muscle coordination may improve in parallel with lifting proficiency.

Prior research has defined high-load in weightlifting as 85% 1RM or greater (Ammar et al., 2018), and has shown that biomechanical characteristics are different at high-load conditions compared to lower-load conditions. In triple extension during power clean, ankle plantar flexion torque is higher and knee extension torque is lower under high-load conditions (≥85% one repetition maximum [1RM]) versus low-load conditions (Kipp et al., 2011). It has also been revealed that the duration time to complete the transition phase (DKB) is longer under high-load versus low-load conditions (Enoka, 1988). These data suggested that adjustment of the timing of DKB execution is important for lifting greater weights. Based on these findings, it is hypothesized that power clean under high-load conditions may contribute more to the ankle plantar flexors than to the knee extensors during triple extension compared with power clean under low-load conditions. In addition, it has been reported that DKB causes unweighting (negative impulse) and that the duration time of DKB increases with

CONTACT Benio Kibushi kibushi.b@ruby.kobe-u.ac.jp Development and Environment, Kobe University, Tsurukabuto, Nada-ku, Kobe, Japan; Junichi Okada jun1okd@waseda.jp Faculty of Sport Sciences, Waseda University, Mikajima, Tokorozawa, Saitama 359-1192, Japan

higher loads (Enoka, 1979, 1988). Therefore, it is considered important to reduce unweighting and increase the net impulse for lifting greater weights. It is possible that skilled lifters minimize unweighting by shortening the time of DKB more than unskilled lifters, even under high-load conditions.

Recently, muscle synergy analysis has been used to quantify muscle coordination. Muscle synergy refers to a concept, in which multiple muscles are controlled as a group (Bernstein, 1967). Numerous studies have shown that multiple muscle activities can be explained by the combination of a small number of muscle synergies or modules (D'Avella et al., 2003; Hagio & Kouzaki, 2014; Kibushi et al., 2020; Tresch et al., 1999). Kibushi et al. (2020) compared experienced and novice lifters about power clean. They found that novices had less ankle plantar flexion torque and lacked the muscle synergy involved in triple extension. Santos et al. (2021) also compared muscle synergies during power clean between novice and experienced weightlifters under relatively low-load conditions. They reported that, although the similarity of recruited muscle synergies was high, the timing of activation differed. Thus, learning the timing of muscle synergy activation is also important for novices to improve their power clean skills under low-load conditions. However, thus far, studies have not compared the muscle synergies of skilled and unskilled lifters under high-load conditions. Moreover, the approach through which unskilled can adjust their muscle synergies to lift greater weights is currently unknown. Furthermore, discussing muscle activity data alone is often problematic. Previous studies on muscle synergy have well described the function of extracted muscle synergy, by combining biomechanical analysis as well. In other words, biomechanical analysis is necessary for a more accurate interpretation of muscle synergy.

Therefore, the purpose of this study was to determine the differences in muscle synergies between skilled and unskilled participants in power clean under various loading conditions. Because a wide range of loads was used in this study, including high-load conditions, the unskilled subjects had to be those who had been continuously performing Olympic lifting, including power clean. A previous study compared skilled and unskilled participants, demonstrating the same number of muscle synergies but different timing of activity (Santos et al., 2021). Unskilled participants need to optimize DKB and triple extension at high loads. The characteristics of muscle synergies at low loads would be similar between the two groups of subjects. However, there would be differences in the timing of activity of muscle synergies related to DKB and triple extension under high-load conditions.

Materials and methods

Participants

Twenty healthy men participated in this study, including 10 competitive weightlifters with at least 4 years of experience in weightlifting (skilled; age: 20.8 ± 1.4 years, height: 168.0 ± 5.3 cm, body mass: 76.6 ± 13.4 kg, 1RM power clean: 121.2 ± 20.5 kg, and 1RM power clean: 1.58 ± 0.17 kg/body mass [mean ± standard deviation]) and 10 unskilled participants (unskilled; age: 25.2 ± 2.9 years, height: 173 ± 3.5 cm, body mass: 70.2 ± 6.2 kg, 1RM power clean: 75.6 ± 14.3 kg, and 1RM power clean: 1.08 ± 0.22 kg/body mass) with at least 1 year of experience in resistance training including Olympic lifting exercise. A participant in the unskilled group was excluded from the analysis because the reflective marker on the anterior superior iliac spine had been detached. Skilled is defined as an athlete who is an active weightlifting competitor, and professionally engaged in the sport, and unskilled is defined as an athlete who has never competed in weightlifting but incorporates Olympic lifting into their daily training. The participants provided written formed consent for their participation in the study after receiving a detailed explanation of the purpose, potential benefits, and risks associated with this investigation. This study was approved by the Local Ethics Review Committee on Human Research of Waseda University, Tokyo, Japan (Approval number: 2021–087).

Experimental setup and data procedures

This study required 2 days for data collection, with the 1RM test of power clean and submaximal power clean test conducted on days 1 and 2, respectively.

On day 1, 1RM test of the power clean was conducted. Subjects performed a warm-up (i.e., 5 minutes of running and dynamic stretching) and performed a power clean with a weight up to 50% of their self-reported 1RM. Next, the load was gradually increased to 60, 80, and 90% of their self-reported 1RM, and added 2.5–5 kg depending on their previous lifts until they reached their 1RM. The test was performed until two consecutive failures. The success criterion was defined as receiving the barbell at a position with the participants' upper thigh above parallel to the ground and standing up.

Submaximal tests sessions were performed at least 48 hours apart from the 1RM tests to permit recovery from fatigue. The warm-up was performed as described above, and three trials were performed at 60%, 70%, 80%, and 90% 1RM obtained through 1RM testing, respectively. The duration of rest intervals between trials was 30–60 seconds, while that of rest intervals between sets was 2–4 minutes.

During the trial, ground reaction force data were obtained at 1000 Hz using a force platform (0625, ACP, Accupower; AMTI, Watertown, MA, USA). Surface electromyograms (EMG) were recorded from 12 muscles on the right side of the body (SX-230; Biometrics, Gwent, UK): soleus (SOL), gastrocnemius medialis (MG), tibialis anterior (TA), vastus lateralis (VL), adductor magnus (AM), tensor fasciae latae (TFL), biceps femoris long head (BF), semitendinosus (ST), gluteus medius (Gmed), gluteus maximus (Gmax), erector spinae (ES), and upper trapezius (Trap). Prior to the electrode placement, the skin surface was shaved, lightly abraded, and cleaned with an alcohol solution to minimize the impedance of the skin. The electrode placement was carefully selected to minimize crosstalk from the adjacent muscles. We placed the EMG electrodes based on the suggestion from the surface EMG for a non-invasive assessment of muscle (SENIAM) (Hermens et al., 2000). Also, we confirmed all electrodes, including the TA, did not interfere with the barbell trajectory as much as possible.

Kinematic data were recorded by using a three-dimensional optical motion capture system (OptiTrack, NaturalPoint Inc., Corvallis, OR, USA) with 10 cameras operating at 100 Hz. Reflective markers were attached on the body to the skin overlying the following landmarks (Dumas et al., 2007; Kipp et al., 2012): vertex of the head, left and right side of the head, forehead, seventh cervicale, acromion, midspine at tenth rib level, suprasternale, glenoid process, tenth ribs, anterior superior iliac spine, lateral and medial humeral epicondyles, ulnar and radial styloid, greater trochanter, lateral and medial femoral epicondyles, lateral and medial malleolus, calcaneous, first and fifth metatarsal heads, and second toe tip. Both ends of the barbell and two markers were attached to a part of each sleeve. Joint angles were expressed as positive for extension and negative for flexion. The output signal from the force plate was synchronously recorded via A/D conversion, along with kinematic and EMG signals. Of note, the frequency for ground reaction force data and EMG data was reduced from 1000 Hz to 100 Hz to match the sampling frequency of the kinematic data (Werner et al., 2021). All these data were time-interpolated over one lifting motion to fit a normalized 200-point time base.

In this study, the movements for power clean were divided into the following three phases: the first pull phase (from the barbell lift-off to the first maximal knee extension), the transition phase (from the first maximal knee extension to the first maximal knee flexion), and the second pull phase (from the first maximal knee flexion to the second maximal knee extension). Notably, the movements, such as the DKB during the transition phase and the triple extension during the second pull phase, are not performed by inexperienced weightlifters (Kibushi et al., 2020; Kipp et al., 2012). Therefore, the analysis in this study was from barbell lift-off to the second pull. The phase in which the ground reaction force was below the system (body + barbell) weight was defined as the unweighting phase, and the vertical impulse in this phase was calculated. The impulse was divided by the system weight to compare loads and subjects. Only one unskilled participant did not perform DKB; hence, this participant was excluded from the comparison of the variables related to DKB (i.e., vertical impulse during the unweighting phase and duration of transition).

EMG procedure

We analysed raw EMG data based on the start-to-stop time of each power clean phase. The data were high-pass filtered (20 Hz, zero-lag fourth-order Butterworth), full-wave rectified, and low-pass filtered (10 Hz, zero-lag fourth-order Butterworth). Subsequently, the EMG was normalized by the peak activity in EMG values for all muscles across all trials and time-interpolated over 200 points (Kibushi et al., 2020; Ting & Macpherson, 2005; Torres-Oviedo et al., 2006). Interpolated EMG data includes the phases from barbell lift-off to maximum knee extension in the second pull (i.e., first pull, transition, second pull) and determined based on kinematic and kinetic data (Kibushi et al., 2020; Nagao & Ishii, 2019). The EMG matrix of 12 muscles × 201 data points was combined for each load (12 muscles × 201 data points × 3 trials) to extract muscle synergies as described below.

Extraction of muscle synergies

We extracted muscle synergies using a non-negative matrix factorization (NMF) algorithm (Lee & Seung, 1999; Tresch et al., 1999) as represented in Equation 1:

$$M = \sum_{i=1}^{N} W_i C_i + \varepsilon (W_i \geq 0, C_i \geq 0) \quad (1)$$

where M ($m \times t$ matrix, where M is the number of muscles and t is the number of samples) is a linear combination of muscle synergies, W ($m \times n$ matrix, where n is the number of synergies) is the time-invariant muscle weighting components, C ($n \times t$ matrix) is the synergy activation coefficient, representing activation synergies by time-variant, and ε is the residual error matrix.

To determine the number of muscle synergies, we calculated the variability accounted for (VAF), which was based on the entire dataset (VAF_{global}) and each muscle VAF (VAF_{local}) for muscle synergies (Equations 2,3). The number of muscle synergies for each dataset was defined as the minimum number of synergies required to achieve a $VAF_{global} > 90\%$ and a $VAF_{local} > 75\%$ (Kibushi et al., 2018a, 2018b; Torres-Oviedo et al., 2006).

$$VAF_{global} = \frac{(EMG_o - EMG_r)^2}{EMG_o{}^2} \times 100 \quad (2)$$

$$VAF_{local} = \frac{\left(EMGo_{(m,i)} - EMGr_{(m,i)}\right)^2}{EMGo_{(m,i)}{}^2} \times 100 \quad (3)$$

where EMG_o is the original dataset of the processed EMG signal and EMG_r is the reconstructed EMG matrix calculated using the NMF algorithm.

The most frequent numbers (MFNs) of the muscle synergies across the 12 trials were determined based on both VAF_{global} and VAF_{local}. The statistical distribution of the MFNs was examined using the Shapiro–Wilk test ($\alpha = 0.05$) and rejected a normal distribution ($p < 0.001$). Subsequently, the Mann–Whitney U test was used to compare the number of MFNs ($p < 0.001$). We determined that the number of muscle synergies was three.

The extracted muscle synergies were sorted based on cosine similarity (Kibushi et al., 2018b; Torres-Oviedo & Ting, 2007). Initial functional sorting was performed for extracted muscle synergies based on the values of cosine similarity across all muscle synergies of each subject. The cosine similarity was calculated based on the similarity of W and/or C vectors to that of an arbitrary reference subject. Muscle synergies were determined using an iterative process, which involves the grouping of pairs with the highest correlation into the same group. If a single synergy of a single participant was classified into two groups, the pair with the largest cosine similarity value was defined as the same synergy. This functional sorting process was conducted with carefully visual inspection to avoid pairing different muscle synergies even if the pairs have the highest correlation.

Assessment of muscle synergies

The comparison of individual EMG patterns and muscle synergy activations was performed using cross-correlation functions.

We calculated absolute lag times to assess differences in the timing of the activations. The lag time evaluates differences in the timing of activation, and calculated at the maximum of the cross-correlation function (r_{max}) using the Matlab "xcorr" function for centred data (option"coeff") (Frère & Hug, 2012; Vaz et al., 2016).

We also quantified the centre of activity (CoA) of the muscle synergy activation coefficient using circular statistics (Batschelet, 1981). CoA was plotted in polar coordinates, and the vector denotes the relative time of the PC phase (Berens, 2009; Sylos-Labini et al., 2014). The CoA was calculated as the angle of the vector (first trigonometric moment) that points to the centre of the mass of that circular distribution using the following formulae:

$$A = \sum_{t=1}^{N} (\cos \theta_t \times Act_t) \quad (4)$$

$$B = \sum_{t=1}^{N} (\sin \theta_t \times Act_t) \quad (5)$$

$$CoA = tan^{-1}(B/A) \quad (6)$$

where θ_t is the angle at time t (0–100 points) converted from one trial (0–100%) into the angle θ (0–360º); $Act_t$is the activity amplitude of muscle synergy at time t. The CoA was calculated in polar coordinates as the inverse tangent of B/A.

The components of the muscle synergy vector were quantified using 95% confidence interval (CI) (Hayes et al., 2014; Sawers et al., 2015). Significantly active muscles were computed based on the 95% CI because the contribution of each muscle did not include zero, i.e., the value of elements W_{ij} of each muscle i in each synergy vector j extracted from the original EMG datasets using NMF.

We performed a cross-validation to verify the extracted muscle synergies were consistent across groups (Cheung et al., 2005; Hug et al., 2011). We checked whether the muscle synergy vectors of the unskilled subjects adequately explained the EMG patterns of the skilled subjects. To do this, the muscle synergy vectors of the unskilled subject was held fixed in the algorithm and the activation coefficient matrix was free to vary. This procedure was repeated 20 times and we verified the goodness of fit between the original EMG and recomputed EMG data matrix by using VAF.

Statistical analysis

To assess the reliability of the extracted muscle synergies, we calculated the intraclass correlation coefficients ($ICC_{(3,k)}$), which were categorized as follows: 0.9–1.00, excellent; 0.75–0.9, high; 0.5–0.75, moderate; < 0.5, poor (Koo & Li, 2016). The normality of the datasets was verified using the Shapiro–Wilk test. The difference in 1RM power clean between skilled and unskilled participants was tested using independent-samples *t*-tests. Two-way repeated measures analysis of variance was used to compare the magnitudes of DKB and the net vertical impulse between the skilled and unskilled participants at each load. *Post hoc* pairwise comparisons were performed with the Bonferroni method. Within-subject differences (load) were treated as repeated measures, and the sphericity was evaluated using the Mauchly test. If sphericity was not assumed, Greenhouse–Geisser correction was applied to the degrees of freedom. We used one-sample t-tests to evaluate the time lag of individual EMG patterns and the activation coefficient for between-group differences (with zero as the reference value).

For all tests, $p < 0.05$ denoted statistical significance. The effect size was determined using Cohen's *d* (small: > 0.2, moderate: > 0.5, large: > 0.8). All statistical analyses were performed using the SPSS version 27 software (IBM Corp., Armonk, NY, USA).

Results

Participants

A participant in the unskilled group was excluded from the analysis because the reflective marker on the anterior superior iliac spine had been detached. The 1RM power clean was 121.3 ± 20.5 kg (1.59 ± 0.17 kg/BW) and 74.2 ± 14.2 kg (1.07 ± 0.22 kg/BW) for the skilled ($n = 10$) and unskilled ($n = 9$) participants. These results indicated that participants in the skilled group were significant stronger than those in the unskilled group ($p < 0.001$).

Kinematics and kinetics

DKB motion was observed in all participants, except for one unskilled participant. DKB movement during the transition phase, the difference between the first maximum knee joint extension angle and the first maximum flexion angle, was defined as the magnitude of DKB (Figure 1). The unskilled subjects had significantly greater DKB movements than the skilled subjects ($p < 0.05$). Furthermore, the DKB magnitude of unskilled subjects at 90% 1RM was significantly larger than that recorded at 60–80% 1RM ($p < 0.05$). In contrast, there were no significant differences found among the skilled participants at any load.

Table 1 shows the results of the net vertical impulse for the unweighting phase of the power clean. Net values were obtained after subtracting the weight of the system. There was a significantly larger net vertical impulse in the unweighting phase associated with DKB in the 60–90% 1RM range for skilled versus unskilled participants. This finding indicated that the skilled group is less unweighted than the unskilled group during DKB. Figure 2 shows the time required to complete the transition phase (duration) relative to the total lift. In the skilled subjects, there was no difference between any of the loads ($p = 0.753$). However, in the unskilled subjects, only the 90% 1RM had a significantly longer duration than the 60–80% 1RM load ($p < 0.05$).

Extracted muscle synergy

The MFNs of muscle synergy were three (2.6 ± 0.51, $p < 0.001$). Three muscle synergies accounted for 93.3 ± 3.3% in the skilled group and 93.2 ± 0.3% of the entire datasets in the skilled and unskilled groups, respectively. At this number, the condition of $VAF_{global} > 90\%$ was satisfied for all trials. An excellent reliability

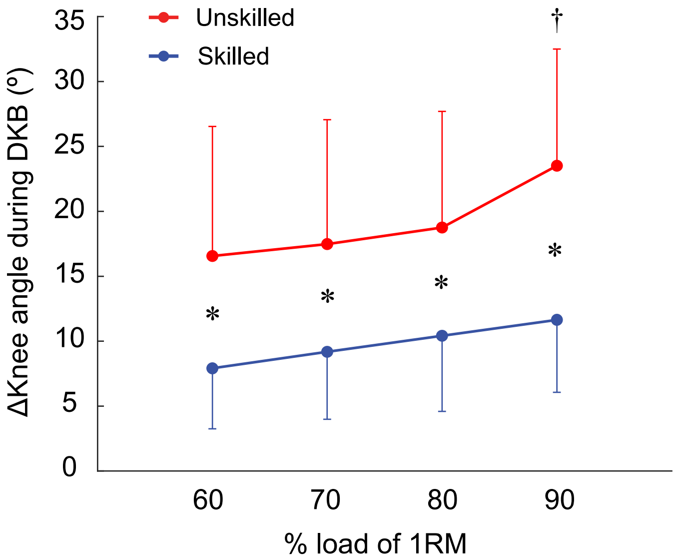

Figure 1. Magnitude of DKB. The Δknee angle represents the magnitude of DKB. The magnitude of DKB was defined as the difference between the maximum knee joint extension angle and the maximum knee joint flexion angle. 0° indicates that DKB did not occur. Blue and red indicate skilled ($n = 10$) and unskilled ($n = 8$) participants, respectively. * Significant difference between skilled and unskilled participants ($p < 0.05$). † Significant difference between 90% 1RM and 60, 70 ,80% 1RM ($p < 0.05$). Abbreviations: 1RM, one repetition maximum; DKB, double-knee bend.

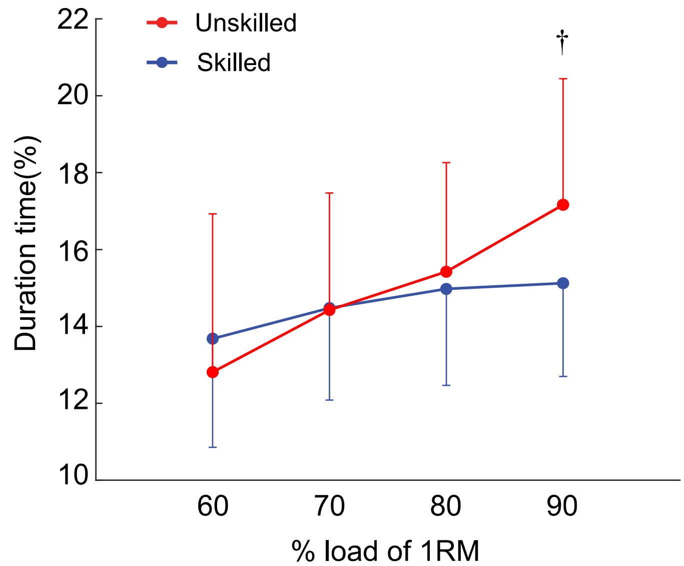

Figure 2. Duration of the transition phase. This phase is defined as the time from the first maximum knee extension to the first maximum knee flexion; it is expressed as a relative value for the entire power clean phase. Blue and red indicate skilled ($n = 10$) and unskilled ($n = 8$) participants, respectively. One of the unskilled participants did not exhibit DKB. † Significant difference between 90% 1RM and 60,70,80%1RM ($p < 0.05$) Abbreviations: 1RM, one repetition maximum; DKB, double-knee bend.

Table 1. Vertical impulse during the unweighting phase of power clean (mean ± SD). Skilled: $n = 10$. Unskilled $n = 8$ (one participant did not exhibit DKB).

	Vertical Impulse during Unweighting Phase (N·s)	
Load (%)	Skilled	Unskilled
60	−7.6 ± 3.4*	−17.8 ± 3.8
70	−5.9 ± 2.6*	−15.7 ± 2.9
80	−5.4 ± 2.9*	−16.2 ± 3.2
90	−4.1 ± 3.4*	−17.0 ± 3.8

*Significant difference between skilled and unskilled participants ($p < 0.05$).
Abbreviations: DKB, double-knee bend; SD, standard deviation.

was shown for the VAF_{Global} of the extracted muscle synergies (ICC: 0.76). The cross-validation procedure showed that the muscle synergy vector of the unskilled accounted for an average *VAF* of 92.0% of the original EMG matrix of the skilled. Each individual muscles in unskilled were also sufficient to explain of muscles in skilled for all loads (VAF_{muscle} ranged from 76.2% to 97.8% for TA and Trap, respectively). Thus, the extracted muscle synergies in both groups were found to be similar. The extracted muscle synergies and activation coefficient across all loads were composed of entire muscle and were very similar across muscle synergies; however, the timing of activation differed (Figure 3). Muscle synergy 1 was activated at 30–40% and 20–30% of the PC in the skilled and unskilled groups, respectively. This result indicated activation during the first pull phase of the power clean. Muscle synergy 2 was activated during the transition phase at 65–70% and 60–65% of the power clean in the skilled and unskilled groups, respectively. The first maximal knee extension appeared at the 60–70% of the power clean. Muscle synergy 3 was activated during the execution of the DKB, as the CoA existed between 70–80% and 75–80% in the skilled and unskilled groups, respectively; the first maximal knee flexion appeared at 70–85% (Figure 4). In the unskilled group, the weighting of muscle synergy 3, SOL, MG, and VL did not significantly active only at 90% 1RM (Figure 5).

Timing of activation coefficient

Table 2 shows the lag time for the same muscle synergies between skilled and unskilled groups, using zero as the reference. Significant lags between groups were observed for muscle synergies 2 and 3 had at all loads. For muscle synergy 2, the timing of activation was earlier in the unskilled group versus the skilled group (average: 6.6 ± 14.2%) at all loads. For TA, the timing of activation was earlier in the unskilled group versus the skilled group (average: 3.3 ± 3.2%) at all loads. Muscle synergy 3 occurred earlier in skilled versus unskilled participants (average: −3.4% ± 3.7%) at all loads. For SOL, MG, VL, AM, BF, ST, Gmed, the timing of activations was earlier in the skilled group versus unskilled group (average: −3.9 ± 2.2%, −3.7 ± 2.2%, −2.6 ± 0.8%, −5.5 ± 0.6%, −4.5 ± 0.8%, −5.9 ± 1.0%, −4.4 ± 1.3%, respectively) at all loads. There was no significant delay observed for muscle synergy 1 between groups (average: 1.2 ± 10.0%).

Discussion

This study aimed to determine the differences in muscle synergy between skilled and unskilled participants in power clean. As shown in Table 1, The unweighting during DKB was lower in skilled versus unskilled participants at all loads. Our findings revealed that, in the skilled group, ankle plantar flexors and knee extensors were significantly active in muscle synergies involved in DKB at high loads (Figure 5). This indicated a potential increase in lower extremity joint stiffness. Therefore, skilled individuals may regulate muscle synergy to lift greater

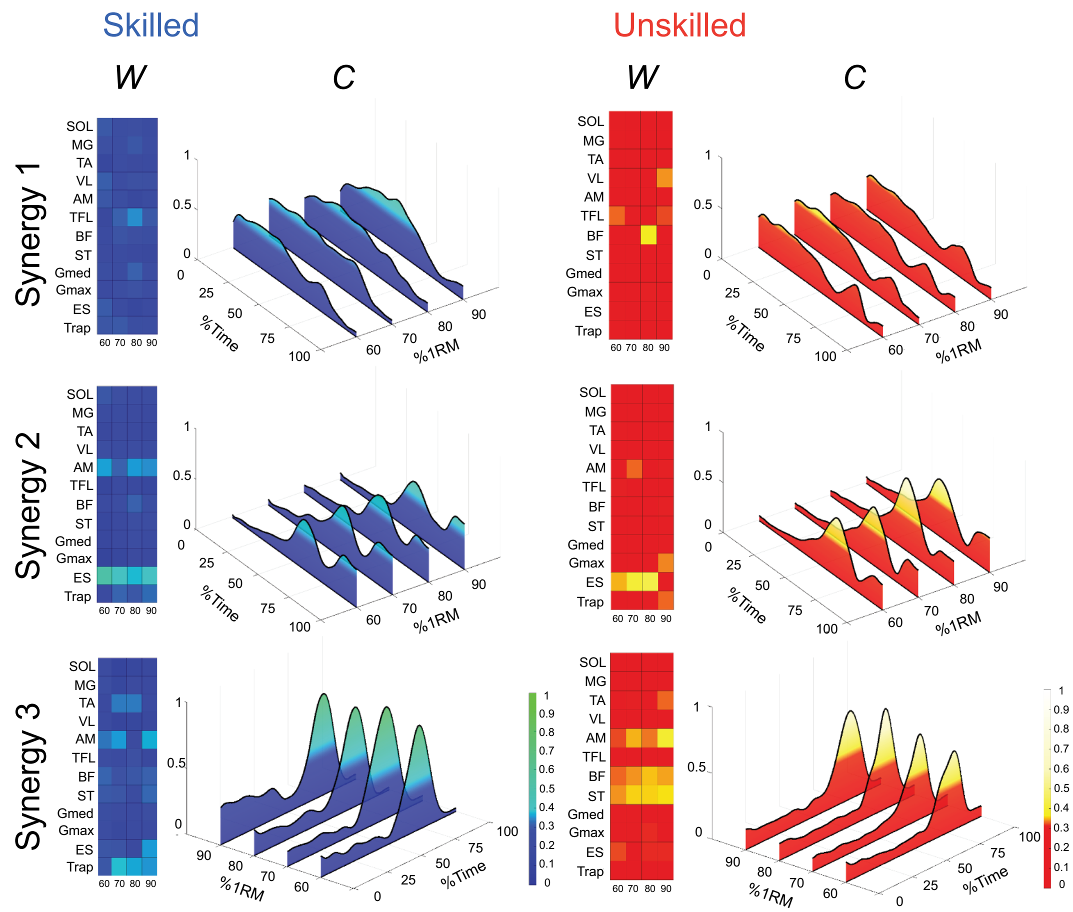

Figure 3. Muscle synergies and activation coefficient under all conditions. The muscle synergies extracted and their activation coefficients at all loads for both groups are shown. Blue and red indicate skilled ($n = 10$) and unskilled ($n = 9$) participants, respectively. Muscle synergies (W) are a spatial component and are illustrated in the heat maps. Each colour map represents the weighting of a muscle between 0 and 1, with higher values (lighter colours) indicating that the muscle contributed to the composition of that muscle synergy. On the other hand, the activation coefficient (C), indicated by the waveform, is a temporal component, indicating the timing and intensity of the activity of muscle synergy. The vertical axis indicates the level of activity of the muscle synergy, and the bottom two axes indicate the time and each load. The abbreviations for each muscle in the heat map are soleus (SOL), medial head of gastrocnemius (MG), tibialis anterior (TA), vastus lateralis (VL), adductor magnus (AM), tensor fascia latae (TFL), biceps femoris (BF), semitendinosus muscle (ST), gluteus medius (Gmed), gluteus maximus (Gmax), erector spinae (ES), trapezius muscle upper fibres (Trap), one repetition maximum (1RM).

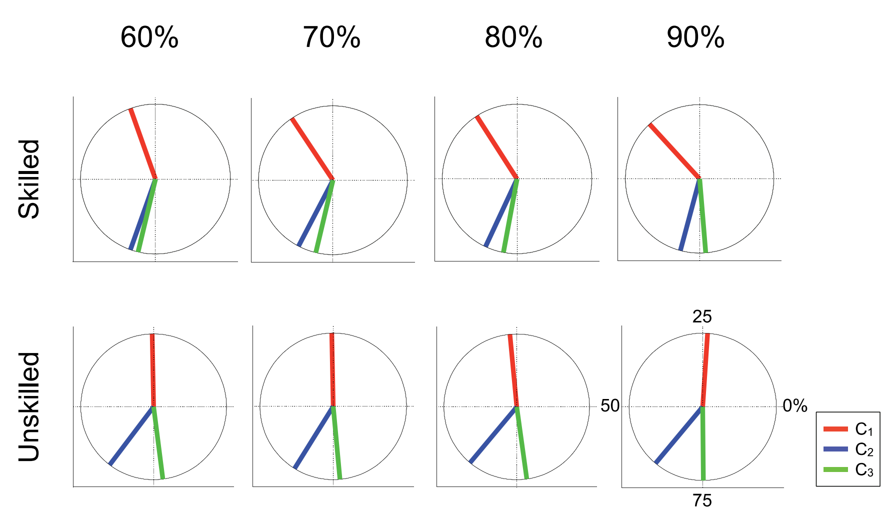

Figure 4. Average CoA among subjects across each load. Average CoA located in polar coordinates and polar direction representing 0–360° in 0–100% of the relative time over the power clean (time progresses counterclockwise). The CoA vector was calculated as the first trigonometric moment of the circular distribution (Batschelet, 1981). The upper panel refers to skilled participants ($n = 10$), while the lower panel refers to unskilled participants ($n = 9$). Abbreviations: CoA, centre of activity.

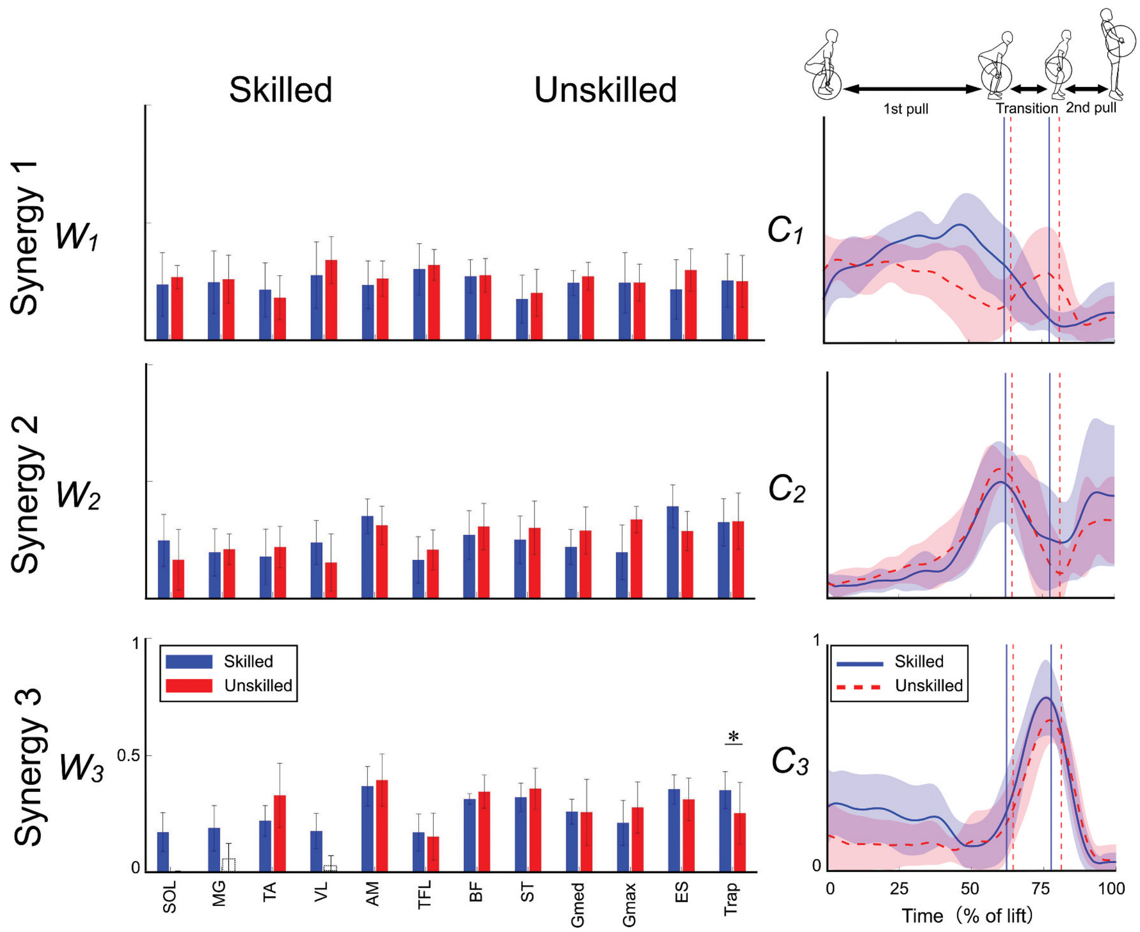

Figure 5. Muscle synergy and activation coefficients for skilled and unskilled participants at 90% 1RM. Blue and red indicate skilled ($n = 10$) and unskilled ($n = 9$) participants, respectively. The muscle weightings (bar) and activations (line) of muscle synergy are shown. Significantly active muscles were represented by filled bars. Non-significantly active muscles were represented by open bars. The asterisks indicate the muscles that differed between skilled and unskilled. Muscles were classified as significantly active if their 95% CI did not include zero. They were classified as non-significantly active if their 95% CI that include zero. The shaded area of activations represents the standard deviation. The first vertical line in C1–C3 represents the timing of the first maximum knee extension, while the second represents the first maximum knee flexion. Abbreviations: 1RM, one repetition maximum; AM, adductor magnus; BF, biceps femoris long head; CI, confidence interval; ES, erector spinae; Gmax, gluteus maximus; Gmed, gluteus medius; MG, gastrocnemius medialis; SOL, soleus; ST, semitendinosus; TA, tibialis anterior; TFL, tensor fasciae latae; Trap, upper trapezius; VL, vastus lateralis.

Table 2. Lag times (%) for the activation coefficient (mean ± SD).

	Load (%)	Lag Time (%)	*p* value	Cohen's *d*
Syn1	60	0.1 ± 5.3	0.928	0.01
	70	1.6 ± 8.5	0.103	0.19
	80	0.5 ± 10.3	0.656	0.05
	90	2.7 ± 15.8	0.148	0.17
Syn2	60	**6.9 ± 16.2**	<0.001	0.42
	70	**7.2 ± 15.2**	<0.001	0.48
	80	**6.2 ± 12.5**	<0.001	0.50
	90	**6.2 ± 12.9**	<0.001	0.48
Syn3	60	**-4.1 ± 4.8**	<0.001	−0.86
	70	**-4.4 ± 3.8**	<0.001	−1.16
	80	**-3.8 ± 3.3**	<0.001	−1.16
	90	**-1.2 ± 2.8**	<0.001	−0.45

Skilled ($n = 10$) and unskilled participants ($n = 9$) were included.
Note: Positive lag time values indicate a backward shift in skilled participants compare with unskilled participants. Bold values represent significant differences from 0 lag.
Abbreviations: SD, standard deviation.

weights under high-load conditions. Our results suggest that unskilled individuals should increase the contribution of ankle plantar flexors and knee extensors to minimize unweighting concerning the muscle synergies involved in DKB; this approach would increase their lifting capacity.

The skilled group had significantly greater 1RM than the unskilled group, which was comparable to that reported in a previous study (Takei et al., 2020). All participants, except one unskilled participant, exhibited DKB. This was evidenced by the extension-flexion-extension behaviour of the knee joint at all loads. Additionally, positive maxima in the foot, knee, and hip angles and angular velocity appeared during the second pull phase. Therefore, the timing of maximal extension was identical in both groups, and they both performed the triple extension. Based on previous research, it can be considered that the unskilled participants had a higher skill level than novice participants, while the skilled subjects had an even higher skill level than the unskilled participants.

During the unweighting phase of the DKB movement, skilled participants exhibited a greater impulse (resulting in less unweighting) compared with unskilled participants (Table 1). Additionally, the magnitude of DKB was higher in unskilled versus skilled participants. In addition, unskilled participants demonstrated significantly greater DKB at 90% 1RM compared with 60–80% 1RM (Figure 1). Smidt (1973) demonstrated that the optimal joint angle for the knee joint extension ranged from 120–145°. In the present study, the skilled and unskilled participants demonstrated a mean maximum knee joint flexion angle of 121.9 ± 1.2° and 135.4 ± 2.3°, respectively, during the transition phase at all loads. Thus, both groups performed DKB at the optimal knee joint angle. However, reducing unweighting during DKB may be advantageous for lifting heavier weights. The net vertical impulse determines the jump height in performance (Kirby et al., 2011). Hence, gaining as much net vertical impulse as possible from the initiation of the movement to the end of the second pull is necessary to lift heavier weights in power clean. Therefore, minimizing DKB in skilled participants may lead to the lifting of heavier weights in power clean. At loads ≥ 90% 1RM, the unskilled participants might have exaggerated their DKB, potentially limiting their lifting capacity.

The extracted muscle synergies in both groups showed no significant difference at 60–80% 1RM. This indicates that similar muscle coordination patterns are recruited in both groups. Dryburgh and Psycharakis (2016) examined muscle activity during power clean using 70–90% 1RM. They report that only the gastrocnemius muscle increased in average muscle activity during the movement with increasing load, with no significant increases in other muscle activities. In other words, if a person is somewhat familiar with Olympic lifting movements, including power cleans, muscle activity may not change significantly at more than moderate loads.

However, muscle synergy 3 involved in DKB, ankle plantar flexors, and knee extensors were significantly active only in skilled subjects at 90% 1RM (Figure 5). This may be attributed to increased ankle and knee joint stiffness during DKB. The extension-flexion-extension movement at the knee joint during DKB is thought to cause SSC (Enoka, 1979; Nagao et al., 2012). Enhanced joint stiffness may improve the efficiency of tendon elastic energy reuse (Komi, 2000). The skilled participants in this study may have enhanced ankle and knee joint stiffness during DKB. This may have improved the efficiency of SSC utilization (e.g., the reutilization of tendon elastic energy). The smaller DKB movements of the skilled participants may also reflect greater stiffness during DKB (Figure 1). Taken together, the results showed that the activity of the ankle plantar flexors and knee extensors during the unweighting phase may inhibit unweighting movements, while simultaneously augmenting joint stiffness. This finding suggests that contribution by the ankle plantar flexors and knee extensors during DKB may be effective strategy for lifting greater weights. In other words, muscle synergy 3 involved in DKB plays a critical role in regulating the contribution of ankle plantar flexors and knee extensors. Furthermore, the weighting of trapezius muscle in synergy 3 was significantly greater for skilled than for unskilled subjects ($p < 0.05$). Nagao and Ishii (2019) reported on the role of the trapezius muscle in the transition phase body-barbell system, reporting that it plays a role in preventing scapular depression and abduction associated with the downward acceleration of the system. Therefore, it is possible that the unskilled participants in this study were unable to mobilize the upper trapezius well during the execution of the DKB, limiting the lifting weights. Unskilled individuals may be able to enhance their lifting capacity in power clean by acquiring such muscle synergies.

The activation timing of muscle synergy 2 involved in transition and the second pull was earlier in unskilled versus skilled participants (Table 2). This earlier timing of activation may be attributed to the greater DKB of unskilled versus skilled participants (Figure 1). Based on the results of the individual EMG pattern, the earlier timing activation of TA in unskilled subjects may have contributed to the earlier timing of muscle synergy 2. As the ankle joint is dorsiflexed during the transition phase, muscle synergy 2 may have been reflected TA muscle activity specifically. Previous biomechanical studies on weightlifting movements have not investigated the optimal transition phase motion. Stone et al. (2006) found that > 99% of elite weightlifters in the top five U.S. and British national and international competitions performed DKB during the transition phase and reported shorter transition phases than unskilled weightlifters. The duration of the transition phase did not differ significantly between the two groups in this study. Nevertheless, in unskilled participants, the duration for 90% 1RM was significantly longer than that for 60–80% 1RM (Figure 2). At loads ≥ 90%1RM, the unskilled individuals may spend a longer period of time in the transition phase, thereby potentially impeding the DKB movement and limiting their ability to lift greater weights. Therefore, instructors and athletes should pay attention to the duration of the DKB movement. DKB involves ankle and knee joint extension-flexion-extension movements. This movement pattern may involve a concentric-eccentric-concentric contraction in the quadriceps and triceps surae. By improving their eccentric muscle strength during the initial knee extension and flexion, unskilled individuals may reduce the time required to complete the transition phase. Additionally, enhancing the rate of force development and efficiency of SSC utilization during the subsequent extension may also be beneficial (Laffaye & Wagner, 2013; Stone et al., 2006).

The function of muscle synergy in the present study differed from that reported in previous studies, possibly due to variations in participants or techniques. Kibushi et al. (2020) reported that muscle synergy involved in the triple extension was absent in novices about power clean. In contrast, in the current study, even unskilled participants exhibited the triple extension. Santos et al. (2021) also demonstrated that muscle synergies were primarily extracted from the hip extensors, upper limb flexors, and trunk muscles using a touch-and-go method. Power clean was executed as a continuous experimental trial, including the turnover and catch phases after the second pull phase. The muscle activity analysed in this study was predominantly derived from the lower limbs, and the analysis was restricted to the second pull phase. These conditions may have contributed to differences observed in the identified muscle synergies. Weightlifting competitions focus on the maximum lifting weight; thus, it is essential to implement a strategy that can manage heavier loads. In this study, the participants lifted weights up to 90% 1RM, close to their maximum lifting weight. Although the electrodes may have interfered with the subject's movement and the trajectory of the barbell, we tried to reduce movement restriction by using thinner electrodes. In addition, since the participants did not observe the barbell significantly move away from the body to avoid the electrodes, it is thought that there was little restriction of movement by the electrodes.

Since the relative loads were used in both groups, the impact of muscle strength can be discounted. Hence, differences in muscle synergy could be attributed to the skill level of participants.

In the present study, skilled participants showed lower levels of unweighting than unskilled participants. It has been reported that DKB does not occur and lacks the unweighting phase (Nagao et al., 2012); thus, it is difficult to regard this phase as an unnecessary movement. Therefore, it is possible that an optimal amount of unweighting may be necessary for efficiently performing power clean. However, the relationship between the reduction in vertical impulse associated with the unweighting phase and the subsequent increase in the ground reaction force during the second pull phase remains unclear. Another limitation is that the SSC was not quantified in this study. To the best of our knowledge, no previous study has directly quantified whether SSC is utilized during weightlifting. It is difficult to investigate muscle-tendon dynamics during weightlifting trials because the barbell passes over the front of the body. Furthermore, multiple factors are involved in SSC, including stretch reflexes as well as reutilization of tendon elastic energy. We focused on the tendino-muscular system based on muscle activity, and it is possible that spinal excitability is greater in skilled subjects. However, resistance training does not alter h-reflex and may not affect reflex activity (Siddique et al., 2020). Development of reasonable mathematical methods and equipment for the estimation of SSC function is expected in the future.

Conclusion

The purpose of this study was to determine differences in muscle synergy between skilled and unskilled participants in power clean. The unskilled subjects in this study had a higher skill level than the unskilled subjects in previous studies, allowing us to examine differences under high-load conditions. The results revealed that the skilled participants had muscle synergy that contributed to ankle plantar flexors and knee extensors during DKB. This strategy that minimized the negative impulse during the unweighting phase.

Acknowledgments

The authors would like to thank all participants who voluntarily participated in this study.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

Benio Kibushi http://orcid.org/0000-0001-7015-1806

References

Ammar, A., Riemann, B. L., Masmoudi, L., Blaumann, M., Abdelkarim, O., & Hökelmann, A. (2018). Kinetic and kinematic patterns during high intensity clean movement: Searching for optimal load. *Journal of Sports Sciences*, *36*(12), 1319–1330. https://doi.org/10.1080/02640414.2017.1376521

Batschelet, E. (1981). *Circular statistics in biology*. Academic Press.

Berens, P. (2009). CircStat: A MATLAB toolbox for circular statistics. *Journal of Statistical Software*, *58*(10), 293–295. https://doi.org/10.18637/jss.v031.i10

Bernstein, N. A. (1967). *The coordination and regulation of movements*. Pergamon.

Cheung, V. C. K., D'Avella, A., Tresch, M. C., & Bizzi, E. (2005). Central and sensory contributions to the activation and organization of muscle synergies during natural motor behaviors. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *25*(27), 6419–6434. https://doi.org/10.1523/JNEUROSCI.4904-04.2005

D'Avella, A., Saltiel, P., & Bizzi, E. (2003). Combinations of muscle synergies in the construction of a natural motor behavior. *Nature Neuroscience*, *6*(3), 300–308. https://doi.org/10.1038/nn1010

Dryburgh, I., & Psycharakis, S. G. (2016). Muscle activation under different loading conditions during the power clean. *International Journal of Performance Analysis in Sport*, *16*(2), 464–474. https://doi.org/10.1080/24748668.2016.11868901

Dumas, R., Chèze, L., & Verriest, J. P. (2007). Adjustments to McConville et al. and young et al. body segment inertial parameters. *Journal of Biomechanics*, *40*(3), 543–553. https://doi.org/10.1016/j.jbiomech.2006.02.013

Enoka, R. M. (1979). The pull in Olympic weightlifting. *Medicine and Science in Sports*, *11*(2), 131–137 .

Enoka, R. M. (1988). Load- and skill-related changes in segmental contributions to a weightlifting movement. *Medicine & Science in Sports and Exercise*, *20*(2), 178–187. https://doi.org/10.1249/00005768-198820020-00013

Frère, J., & Hug, F. (2012). Between-subject variability of muscle synergies during a complex motor skill. *Frontiers in Computational Neuroscience*, *6*, 1–13. https://doi.org/10.3389/fncom.2012.00099

Hackett, D., Davies, T., Soomro, N., & Halaki, M. (2016). Olympic weightlifting training improves vertical jump height in sportspeople: A systematic review with meta-analysis. *British Journal of Sports Medicine*, *50*(14), 865–872. https://doi.org/10.1136/bjsports-2015-094951

Hagio, S., & Kouzaki, M. (2014). The flexible recruitment of muscle synergies depends on the required force-generating capability. *Journal of Neurophysiology*, *112*(2), 316–327. https://doi.org/10.1152/jn.00109.2014

Haug, W. B., Drinkwater, E. J., & Chapman, D. W. (2015). Learning the hang power clean: Kinetic, Kinematic, and technical changes in four weightlifting naive athletes. *Journal of Strength & Conditioning Research*, *29*(7), 1766–1779. https://doi.org/10.1519/JSC.0000000000000826

Hayes, H. B., Chvatal, S. A., French, M. A., Ting, L. H., & Trumbower, R. D. (2014). Neuromuscular constraints on muscle coordination during overground walking in persons with chronic incomplete spinal cord injury. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*, *125*(10), 2024–2035. https://doi.org/10.1016/j.clinph.2014.02.001

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology*, *10*(5), 361–374. https://doi.org/10.1016/S1050-6411(00)00027-4

Hug, F., Turpin, N. A., Couturier, A., & Dorel, S. (2011). Consistency of muscle synergies during pedaling across different mechanical constraints. *Journal of Neurophysiology*, *106*(1), 91–103. https://doi.org/10.1152/jn.01096.2010

Kibushi, B., Hagio, S., Moritani, T., & Kouzaki, M. (2018a). Lower local dynamic stability and invariable orbital stability in the activation of muscle synergies in response to accelerated walking speeds. *Frontiers in Human Neuroscience*, *12*, 1–14. https://doi.org/10.3389/fnhum.2018.00485

Kibushi, B., Hagio, S., Moritani, T., & Kouzaki, M. (2018b). Speed-dependent modulation of muscle activity based on muscle synergies during treadmill walking. *Frontiers in Human Neuroscience*, *12*, 1–13. https://doi.org/10.3389/fnhum.2018.00004

Kibushi, B., Sado, N., & Kouzaki, M. (2020). Absent muscle coordination patterns and reduced force exertion in the novice of clean exercise. In ISBS Proceedings Archive. (pp. 276–279). Northern Michigan University.

Kipp, K., Harris, C., & Sabick, M. B. (2011). Lower extremity biomechanics during weightlifting exercise vary across joint and load. *The Journal of Strength & Conditioning Research*, *25*(5), 1229–1234. https://doi.org/10.1519/JSC.0b013e3181da780b

Kipp, K., Redden, J., Sabick, M., & Harris, C. (2012). Kinematic and kinetic synergies of the lower extremities during the pull in Olympic weightlifting. *Journal of Applied Biomechanics*, *28*(3), 271–278. https://doi.org/10.1123/jab.28.3.271

Kirby, T. J., McBride, J. M., Haines, T. L., & Dayne, A. M. (2011). Relative net vertical impulse determines jumping performance. *Journal of Applied Biomechanics*, *27*(3), 207–214. https://doi.org/10.1123/jab.27.3.207

Komi, P. V. (2000). Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. *Journal of Biomechanics*, *33*(10), 1197–1206. https://doi.org/10.1016/S0021-9290(00)00064-6

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability Research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Laffaye, G., & Wagner, P. (2013). Eccentric rate of force development determines jumping performance. *Computer Methods in Biomechanics and Biomedical Engineering*, *16*(sup1), 82–83. https://doi.org/10.1080/10255842.2013.815839

Lee, D. D., & Seung, H. S. (1999). Learning the parts of objects by non-negative matrix factorization. *Nature*, *401*(6755), 788–791. https://doi.org/10.1038/44565

Nagao, H., & Ishii, Y. (2019). Characteristics of the shrug motion and trapezius muscle activity during the power clean. *Journal of Strength and Conditioning Research*. https://doi.org/10.1519/JSC.0000000000003355

Nagao, H., Yamada, H., Ogawara, K., Aruga, S., & Koganesawa, K. (2016). Study of force production in quick lift training motion by comparison between skilled and unskilled subjects. *Journal of the Society of Biomechanics of Japanese*, *23*, 161–172. https://doi.org/10.3951/biomechanisms.23.161

Nagao, H., Yamada, H., Ogawara, K., Miyazaki, S., Aruga, S., & Koganezawa, K. (2012). Dynamical study on lower limb during the power clean - difference between skilled and unskilled-. *Japanese Journal of Biomechanics in Sports and Exercise*, *16*, 206–219. https://doi.org/10.32226/jjbse.2012_008

Santos, P. D. G., Vaz, J. R., Correia, P. F., Valamatos, M. J., Veloso, A. P., & Pezarat-Correia, P. (2021). Intermuscular coordination in the power clean exercise: Comparison between Olympic weightlifters and untrained individuals—a preliminary study. *Sensors*, *21*(5), 1904–1916. https://doi.org/10.3390/s21051904

Sawers, A., Allen, J. L., & Ting, L. H. (2015). Long-term training modifies the modular structure and organization of walking balance control. *Journal of Neurophysiology*, *114*(6), 3359–3373. https://doi.org/10.1152/jn.00758.2015

Siddique, U., Rahman, S., Frazer, A. K., Pearce, A. J., Howatson, G., & Kidgell, D. J. (2020). Determining the sites of neural adaptations to resistance training: A systematic review and meta-analysis. *Sports Medicine*, *50*(6), 1107–1128. https://doi.org/10.1007/s40279-020-01258-z

Smidt, G. L. (1973). Biomechanical analysis of knee flexion and extension. *Journal of Biomechanics*, *6*(1), 79–92. https://doi.org/10.1016/0021-9290(73)90040-7

Stone, M. H., Pierce, K. C., Sands, W. A., & Stone, M. E. (2006). Weightlifting: A brief overview. *Strength & Conditioning Journal*, *28*(1), 50–66. https://doi.org/10.1519/00126548-200602000-00010

Sylos-Labini, F., La Scaleia, V., D'Avella, A., Pisotta, I., Tamburella, F., Scivoletto, G., Molinari, M., Wang, S., Wang, L., van Asseldonk, E., van der Kooij, H., Hoellinger, T., Cheron, G., Thorsteinsson, F., Ilzkovitz, M., Gancet, J., Hauffe, R., Zanov, F., Lacquaniti, F., & Ivanenko, Y. P. (2014). EMG patterns during assisted walking in the exoskeleton. *Frontiers in Human Neuroscience*, *8*, 1–12. https://doi.org/10.3389/fnhum.2014.00423

Takei, S., Hirayama, K., & Okada, J. (2020). Is the optimal load for maximal power output during hang power cleans submaximal? *International Journal of Sports Physiology & Performance*, *15*(1), 18–24. https://doi.org/10.1123/ijspp.2018-0894

Ting, L. H., & Macpherson, J. M. (2005). A limited set of muscle synergies for force control during a postural task. *Journal of Neurophysiology*, *93*(1), 609–613. https://doi.org/10.1152/jn.00681.2004

Torres-Oviedo, G., Macpherson, J. M., & Ting, L. H. (2006). Muscle synergy organization is robust across a variety of postural perturbations. *Journal of Neurophysiology*, *96*(3), 1530–1546. https://doi.org/10.1152/jn.00810.2005

Torres-Oviedo, G., & Ting, L. H. (2007). Muscle synergies characterizing human postural responses. *Journal of Neurophysiology*, *98*(4), 2144–2156. https://doi.org/10.1152/jn.01360.2006

Tresch, M. C., Saltiel, P., & Bizzi, E. (1999). The construction of movement by the spinal cord. *Nature Neuroscience*, *2*(2), 162–167. https://doi.org/10.1038/5721

USA Weightlifting Association. (2015). *Weightlifting & Sport performance coaching course manual*. USA Weightlifting.

Vaz, J. R., Olstad, B. H., Cabri, J., Kjendlie, P. L., Pezarat-Correia, P., & Hug, F. (2016). Muscle coordination during breaststroke swimming: Comparison between elite swimmers and beginners. *Journal of Sports Sciences*, *34*(20), 1941–1948. https://doi.org/10.1080/02640414.2016.1143109

Werner, I., Szelenczy, N., Wachholz, F., & Federolf, P. (2021). How do movement patterns in weightlifting (clean) change when using lighter or heavier barbell loads?—A comparison of two principal component analysis-based approaches to studying technique. *Frontiers in Psychology*, *11*, 1–10. https://doi.org/10.3389/fpsyg.2020.606070