

Whole body muscle activity during weightlifting exercise evaluated by positron emission tomography

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Research article

Keywords: HPC, FDG, weight, rest intervals, exercise choices, speed, electromyographic (EMG), FDG-PET

Posted Date: June 14th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-612816/v1>

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Abstract

Background

This study investigated the whole-body skeletal muscle activity pattern of hang power clean (HPC), a major weight training exercise, using positron emission tomography (PET).

Method

Twelve college weightlifting athletes performed three sets of HPC 20 times with a barbell set to 40 kg both before and after an intravenous injection of 37 MBq 18F-fluorodeoxyglucose (FDG). PET-computed tomography images were obtained 50 min after FDG injection. Regions of interest were defined within 71 muscles. The standardized uptake value was calculated to examine the FDG uptake of muscle tissue per unit volume, and FDG accumulation was compared to the control group. The Mann–Whitney U-test was used to evaluate the differences in the mean SUV between groups. The difference between SUVs of the right and left muscles was evaluated by a paired t-test. A P-value < 0.05 was considered statistically significant.

Results

FDG accumulation within the vastus lateralis, vastus intermedius, and vastus medialis was higher than that of the rectus femoris. FDG accumulation within the triceps surae muscle was significantly higher only in the soleus. In the trunk and hip muscles, FDG accumulation of only the erector spinae was significantly increased. In all skeletal muscles, there was no difference between SUVs of the right and left muscles.

Conclusions

The monoarticular muscles in the lower limbs were active in HPC. In contrast, deep muscles in the trunk and hip were not active during HPC. HPC is not suitable for core training and needs to be supplemented with other training.

Introduction

Resistance training programs have been extensively studied for training strategies such as weight, rest intervals, exercise choices, and speed [1]. Recently, weightlifting exercises have been gaining attention as exercise choices. Previous studies have reported the effects of weightlifting exercise to improve jump performance, which has been shown to be more effective than conventional resistance training [2, 3]. Most weightlifting exercises are multi-joint exercises, which are considered more effective than single-joint exercises for movements closer to the movement pattern of sports [4]. Hang power clean training (HPC) is one of the major types of weightlifting exercises that involve holding the barbell in the hands while standing and lifting it to the shoulder level using the recoil of the lower limbs (Fig. 1). Hori et al. showed a positive correlation between maximum lifting weight and vertical jump performance [5].

Although many studies have investigated the effects of weightlifting exercises such as HPC on exercise performance, it is not clear what kind of whole-body skeletal muscle activity actually occurs.

Figure 1. The motion of HPC

Muscle activity during various types of training, including weightlifting exercises, has been investigated using electromyographic (EMG) examinations. EMG examinations detect the electric potentials caused by transmembrane currents in muscle fibers and can be defined as electrophysiological recordings. It is possible to compare skeletal muscle activity during exercise [6]. However, EMG examinations have some limitations. In general, it can only test the activity of a limited number of superficial muscles with attached electrodes. Needle electrodes are sometimes used to observe deep parts of the muscle, but they are somewhat invasive. In addition, since the cords that connect to the electrodes hinder exercise, the activity level is disturbed. Therefore, EMG examinations are limited in terms of the number of skeletal muscles that can be evaluated and the types of exercise.

Glucose metabolism during exercise is dependent on muscle power output and muscle mass recruited; tissue uptake of plasma glucose increases in relation to exercise intensity [7, 8]. Fujimoto et al. focused on the mechanism of glucose metabolism in skeletal muscle and reported on glucose uptake in individual skeletal muscles during aerobic running using positron emission tomography (PET) with ^{18}F -fluorodeoxyglucose (FDG) [9, 10]. Subsequent studies have shown that glucose metabolism measured by FDG-PET is highly correlated with skeletal muscle activity intensity [11, 12].

The purpose of this study was to investigate the whole-body skeletal muscle activity pattern of HPC using FDG-PET. Since the knee extension torque has a large effect on the vertical jump performance [13], it was assumed that there was high muscle activity in the quadriceps femoris during HPC.

Materials And Methods

The participants were 12 college weightlifting athletes (age, 21 ± 0.7 years old; height, 168.4 ± 6.0 cm; weight, 82.7 ± 20.1 kg; body mass index (BMI), 28.9 ± 5.8 kg m²), and 10 healthy adults (age, 25.3 ± 3.8 years; height, 172.7 ± 2.9 cm; weight, 76.1 ± 7.6 kg; BMI, 25.5 ± 1.8 kg m²) who were limited to daily activities only. All participants were considered healthy after a review of their medical history and physical examination. The study design was approved by the ethics committee of our institute (approval #2976). The purpose and potential risks of this study were explained to the subjects, and written informed consent was obtained from all participants.

All participants were restricted from strenuous exercise the day before the test. In addition, eating and drinking, except for water, was prohibited from 6 hours before the test. The subjects in the HPC group performed a sufficient warm-up and three sets of HPC 20 times with a barbell set to 40 kg. The subjects were urged to perform one action at intervals of approximately 3 s, and were monitored for no movement other than HPC. Subsequently, FDG was intravenously injected, and three sets of HPC were performed 20 times again. The plasma glucose level of each subject was confirmed to be normal before FDG injection.

The subjects in the control group were placed in the sitting position for 20 min, 37 MBq of FDG was injected intravenously, and they remained seated for another 45 min.

PET analysis

Participants were subsequently placed in a supine position on a scanning bed into the gantry of the PET-CT system (Discovery PET/CT 690; GE Healthcare, Milwaukee, WI, USA). Scanning was performed with a 60-cm axial field of view and a transaxial resolution of 6.4 mm (full-width at half maximum at the center of the field of view without a scattering medium). Before emission scanning, an unenhanced CT scan was performed for attenuation correction and muscle orientation. Emission scanning was performed in 3-dimensional mode 50 min after ^{18}F -FDG administration at 3 min/bed station. The total emission time was 39–42 min. Images were reconstructed with 3-dimensional ordered subset expectation maximization with two iterations and 16 subsets. After reconstruction, a 6.4-mm full-width at half-maximum Gaussian post-filter was applied.

Seventy-one skeletal muscles identified by plain CT axial imaging were used for evaluation. The trapezius and deltoid muscles were evaluated in three parts: upper, middle, and posterior, and anterior, middle, and posterior, respectively. When evaluating each skeletal muscle, landmarks were set to minimize the deviation of the slices to be evaluated. The combination of the set landmark and the evaluated 71 skeletal muscles were as follows: (1) the seventh spinal vertebrae for the upper trapezius as well as the levator scapulae muscles; (2) just above the humerus for the middle trapezius as well as the supraspinatus muscles; (3) center of the femoral head for subscapularis as well as infraspinatus, anterior deltoid, middle deltoid, posterior deltoid, and coracobrachialis muscles; (4) the ninth thoracic vertebrae for the latissimus dorsi muscle; (5) proximal humerus for the lower trapezius as well as the teres minor, pectoralis minor, and serratus anterior muscles; (6) humerus diaphysis for the biceps brachii as well as the triceps brachii and teres major muscles; (7) capitulum for the humerus brachialis as well as the anconeus muscles; (8) distal forearm for the pronator teres as well as the flexor digitorum superficialis, flexor digitorum profundus, pronator quadratus, brachioradialis, and extensor digitorum communis; (9) metacarpal diaphysis of the thumb for the abductor pollicis brevis as well as the adductor hallucis, abductor digiti minimi, and adductor hallucis muscles; (10) proximal phalanx of the thumb for the lumbricalis muscle; (11) fourth lumbar vertebrae for the abdominal rectus as well as the abdominal external oblique, the abdominal internal oblique, the transverse abdominal, the greater psoas, the lumbar quadratus, the erector spinae, and the iliacus muscles; (12) acetabular roof for the gluteus maximus as well as the gluteus medius, the gluteus minimus, the piriformis, and the obturator internus muscles; (13) femoral neck for the obturator externus as well as the tensor fasciae latae muscles; (14) femoral diaphysis for the rectus femoris as well as the vastus lateralis, the vastus intermedius, vastus medialis, sartorius, gracilis, semimembranosus, semitendinosus, biceps femoris muscles, and the adductor muscle complex; (15) head of the fibula for popliteus muscle; (16) tibia diaphysis for the anterior tibia as well as the posterior tibia, extensor hallucis longus, extensor digitorum longus, peroneus longus, peroneus brevis, flexor hallucis longus, flexor digitorum longus, gastrocnemius, and soleus muscles; (17) base of the fifth metatarsal for the abductor hallucis as well as the quadratus plantae and flexor digitorum brevis

muscles; and (18) base of the first metatarsal for the abductor digiti minimi as well as the flexor hallucis brevis, adductor hallucis, and interosseous muscles.

Regions of interest (ROIs) were manually drawn for 71 skeletal muscles. An experienced orthopedic surgeon defined all ROIs using plain CT images and calculated the standardized uptake value (SUV) of FDG. The SUV was calculated to quantitatively examine the FDG uptake of the muscle tissue per unit volume according to the equation: $SUV = \{\text{mean regions of interest count (counts per second/pixel)} \times \text{calibration factor (counts per second/Bq)}\} / \{\text{injected dose (Bq)} / \text{body weight (g)}\}$. ROIs were defined for the right and left sides of the aforementioned skeletal muscles. The mean SUV was calculated using the following equation: $\text{mean SUV} = ([\text{left mean SUV} \times \text{left muscle area}] + [\text{right mean SUV} \times \text{right muscle area}]) / (\text{left muscle area} + \text{right muscle area})$.

Statistical analysis

All data are presented as means and standard deviations. All statistical analyses were performed using IBM SPSS for Windows ver. 25.0. The Mann–Whitney U-test was used to evaluate the differences in the mean SUV between groups. The difference between SUVs of the right and left muscles was evaluated by a paired t-test. A P-value < 0.05 was considered statistically significant.

Results

Regarding the relevant characteristics of the participants, there was a significant difference only in age between the two groups (Table 1).

Table 1. Physical characteristics of the subjects in HPC and Control groups (values are mean ± SD)

Figure 2 illustrates typical whole-body PET images of the HPC groups. A total of 71 skeletal muscles were evaluated by SUV, and 29 had a significant increase in the SUV (Tables 2 and 3). In the upper half of the body, the mean SUV of the middle trapezius, posterior deltoid, and forearm flexor muscles were especially high. In the quadriceps, SUVs of the vastus lateralis, vastus intermedius, and vastus medialis tended to be higher than that of the rectus femoris. In the triceps surae, only the SUV of the soleus significantly increased. In the trunk and hip muscles, only the SUV of the erector spinae was significantly increased. In all skeletal muscles, there was no difference between SUVs of the right and left muscles.

Figure 2. Representative whole-body positron emission tomography images after performance of HPC

Table 2. Difference of mean SUVs from control group in HPC group, neck-lower arm (values are mean ± SD)

Table 3. Difference of mean SUVs from control group in HPC group, trunk-foot

(values are mean ± SD)

Discussion

This is the first study to apply FDG-PET to a weightlifting exercise and comprehensively investigate whole body skeletal muscle activity in HPC. The most important findings of the present study were that in the lower limbs, there was significantly increased muscle activities in the mono-articular muscles, and there was almost no muscle activity in the trunk and hip muscles. These findings provide insightful into improving sports performance and training strategies.

Glucose is one of the energy sources of skeletal muscle; ^{18}F -FDG is taken up by muscle cells like glucose but is not metabolized and remains in muscle cells as FDG-6-phosphate, which is known as metabolic trapping [9, 10, 12]. Since metabolic trapping is preserved for ~2 h after injection [14], FDG-PET reflects skeletal muscle glucose metabolism during exercise. Fujimoto et al. used PET to evaluate muscle activity during running in one of the first PET-based studies on muscle activity during exercise [9]. Other previous studies have investigated PET during more complex tasks requiring endurance such as running [15] and double poling [16]. Bojsen-Møller et al. proposed that PET imaging might be a promising adjunct modality or alternative to more traditional methods for investigating muscle activity during complex human movements [16]. Our group applied FDG-PET to the FIFA 11 training program and reported on muscle activity during training and continued effects [17, 18]. We also evaluated the muscle activity of the lower limbs using the belt electrode skeletal muscle electrical stimulation system and demonstrated the effectiveness of FDG-PET in passive exercise [19].

In the cervical, dorsal, and deltoid muscles, there was significant muscle activity in the posterior deltoid and teres major muscles related to adduction and extension of the shoulder. There was also significant muscle activity in the middle part of the trapezius and rhomboid muscles related to adduction of the scapula.

In the upper limbs, significant muscle activity was observed in the muscles related to elbow flexion, and the grip of the barbell is considered to contribute to the flexor muscles of the forearm. The muscle activity of the extensor digitorum may be due to the dorsiflexion of the wrist joint held after raising the barbell.

In the trunk and hip muscles, significant muscle activity was observed only in the erector spinae muscles. Previous studies evaluating the EMG activity of the rectus abdominis, external oblique, and erector spinae muscles during squats reported the highest muscle activity in the erector spinae muscles [20], supporting the present results. There was no significant muscle activity in the gluteus muscles, but it affected the hip flexion angle of the HPC. It has been shown that gluteus maximus muscle activity is higher in full squats than in half squats [21].

HPC showed significant muscle activity in the quadriceps femoris. This result was greatly affected by knee extension in the concentric phase. However, when comparing the four muscles of the quadriceps femoris, the mean SUVs of the vastus lateralis, vastus intermedius, and vastus medialis tended to be higher than that of the rectus femoris. Yamashita et al. reported on EMG activities in mono- and bi-articular muscles of the quadriceps femoris when hip and knee extension are combined; they showed that

the EMG activities of the rectus femoris are inhibited and the vastus medialis is facilitated by combining hip extension with knee extension [22]. In addition, Mayer et al. showed that the muscle activity of the vastus lateralis and vastus medialis was higher than that of the rectus femoris during squats; these reports support this result [23]. While squats involve the extension of the hip during the concentric phase, for which the hamstrings are a primary motor, it also involves the extension of the knee, to which the hamstrings are antagonists. Thus, hamstring activity is lower when combined hip and knee extension is performed in comparison to the isolated hip extension [22].

In the triceps surae, the soleus muscle showed significant muscle activity compared to the gastrocnemius muscle. A previous study evaluating muscle activity in the gastrocnemius and soleus muscles during the two-foot hopping task reported that there was muscle activity only in the soleus muscle [24, 25]. The gastrocnemius muscle is a biarticular muscle, and it is possible that muscle activity is inhibited by knee extension.

All subjects had an externally rotated position of the foot during HPC. Because the rectus femoris is the biarticulate muscle, when the foot was externally rotated, the hip was placed in an externally rotated position, potentially activating the rectus femoris. A previous report showed that externally rotated foot position affects rectus femoris muscle activity [26]; this result might have been affected. Peroneal muscle activity is higher in muscles related to plantar ankle flexion, but this result might have been affected by the externally rotated position of the foot.

This study has some limitations. First, the FDG-PET method captures muscle glucose uptake only. Other substrates such as free fatty acids, muscle glycogen, and lactate are also metabolized in the active muscle cells, but glucose oxidation increases with exercise intensity, and glucose uptake increases, to some extent, in proportion to glycogen utilization when exercise intensity rises [10]. In addition, a previous report has shown that FDG uptake is higher in muscles composed of type I fibers than in muscles composed of type II fibers [27]; this result might not completely reflect skeletal muscle activity of HPC. A second limitation of this study is that the SUV measurement method is manual. In addition to the possibility that the range of ROI may not be accurate, the measurement was performed in one slice using the landmark as an index, so it does not reflect the skeletal muscle activity of the entire muscle. The third limitation of this study is that the barbell weight is set low. As mentioned above, plasma glucose uptake in tissues is increased in relation to exercise intensity, so skeletal muscle activity may have been altered by changing the barbell to a heavier weight. However, the heavy barbell could disturb the correct motion of the HPC and lead to athlete injury. Finally, the sample size was limited considering radiation exposure. Sample size was calculated using G-power 3.1 (effect size 1.6, α -error 0.05, and target power 0.95); a minimum of 10 subjects per group was recommended based on a previous study [17].

Although there are the aforementioned limitations, this is the first study to apply FDG-PET to weightlifting exercise. These findings provide useful insight to help in improving sports performance and training strategies.

Conclusion

Whole-body muscle activity during HPC was evaluated from the viewpoint of glucose metabolism using FDG-PET. Skeletal muscle activity of the hippocampus was symmetrical, and many skeletal muscle activities of the upper and lower limbs contributed mainly. The mono-articular muscles in the lower limb were active in HPC; however, the deep muscles in the trunk and hip were not active during HPC. HPC is not suitable for core training and needs to be supplemented with other training.

Abbreviations

BMI: Body mass index; CT: Computed tomography; EMG: Electromyography; FDG: 18F-fluorodeoxyglucose; HPC: Hang power clean; PET: Positron emission tomography; ROI: Regions of interest; SD: Standard deviation; SUV: Standardized uptake value

Declarations

Acknowledgements

This study would not have been possible without participants' cooperation.

Authors' contributions

The study was designed by RY, JN, TM, YT, KS, KA, KT, MK, SK, and TH. All data were analyzed by RY. Data interpretation and manuscript preparation were undertaken by all authors. All authors read and approved the final manuscript. All authors read and approved the final manuscript.

Funding

There is no funding body in the design of the study and collection, analysis, and interpretation of data and in writing the manuscript.

Availability of data and materials

A part of data generated or analyzed during this study are included in this published article [and its supplementary information files]. The complete datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

The study design was approved by the ethics committee of our institute (approval #2976). The purpose and potential risks of this study were explained to the subjects, and written informed consent was obtained from all participants.

Consent for publication

The research participation agreement also included an item of public consent.

Competing interests

The authors declare that they have no competing interests.

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Tables

Due to technical limitations, table 1, 2, 3 is only available as a download in the Supplemental Files section.

Figures



Figure 1

The motion of HPC

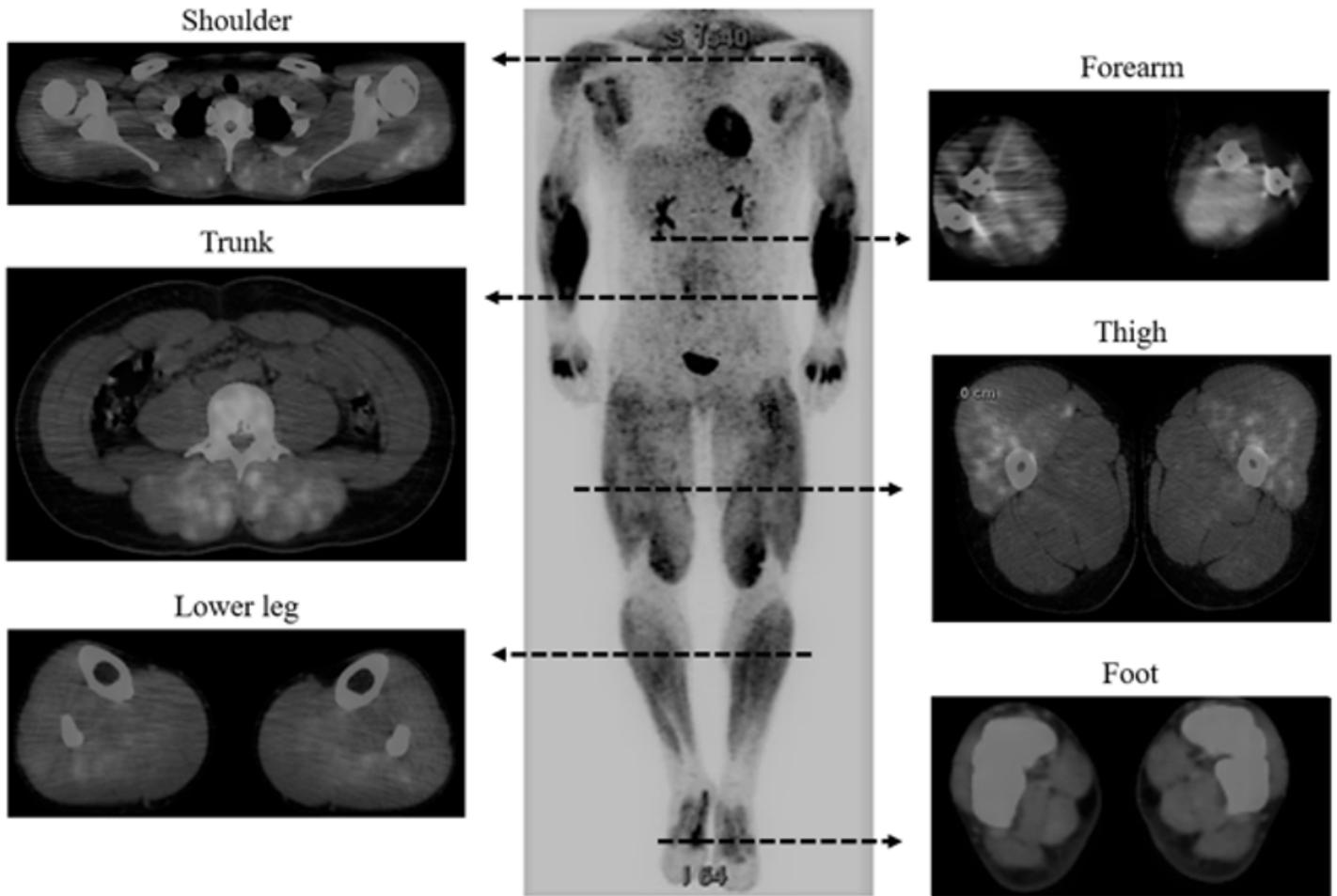


Figure 2

Representative whole-body positron emission tomography images after performance of HPC

Supplementary Files

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