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The performance enhancement of professional weightlifters and treatment of patella tendinopathy in competitive sports athletes

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Propose acceptance (yes / no)

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Content

Abstract

Male weightlifting is a sport with a long history dating back to being included in the first Olympic Games in 1896. In weightlifting, athletes use their reasonable technique, physical, functional and psychological traits to lift a barbell of maximal weight. The achievement of better sports performance is closely related to sports technique and success rate. The sufficient reserve of elite athletes in China provides an adequate ground for my investigation. In addition, Patella tendinopathy is currently widespread in my athletes, seriously affecting training and competition. Based on these, I will analyze the key techniques of weightlifting, the factors that affect success rate, and the rehabilitation evaluation of patella tendinopathy in my thesis.

The first research question of this thesis: In the past four Olympic Games (2004, 2008, 2012, and 2016) Chinese male athletes have won the gold medals in the 69-kg class of weightlifting. The 69-kg class in China, which is identified as the category with the greatest depth of lifters from top to bottom. The technique of top-elite athletes represents the best performance, and can be considered as excellent technical model or a reference that should be achieved. Previous studies of snatch performance focused mainly on the differences in adult female weightlifters, between adult and adolescent males, and between genders. However, the lack of data regarding the stability of snatch technique raises questions regarding the appropriateness of using the specific assistant exercises for improving the success of the snatch lift. Furthermore, no study was found within the literature that summarized the snatch key technical characteristics of top-elite lifters and compared the snatch performances between top-elite and sub-elite male weightlifters.

The first objective of this thesis: To highlight the differences of technical characteristics between top-elite and sub-elite male weightlifters, to summarize the technical features of top-elite athletes, and to provide valuable information for numerous lower level lifters and coaches to integrate into training and competition.

The second research question of this thesis: In the snatch competition, each athlete only has 3 attempts to lift the barbell, so the success rate is the guarantee for the best

result. There are few studies to compare technical differences of successful and unsuccessful snatch actions in literature. The failed snatch attempts of elite lifters often occurred during the support completion stage (*M6*), therefore, it is speculated that the main reason for failure of forward or backward is that the relative position of the *COG* of barbell and body on the sagittal plan exceeds the lifters' control limit. Since the trajectory of the *COG* of barbell will be different of every attempt of each lifter, and there is a certain relationship between the trajectories of the *COG* of barbell and *COG* of body, the present study proposes to use the human & bar combination barycenter as the research parameter to find the reason of failed attempts.

The second objective of this study: To analyzed the three principles of "Near", "Fast", and "Low" of snatch, the supplement principle of "phases", and the human & bar combination barycenter, to exposit the differences between successful and unsuccessful characteristics of snatch attempts in competition, and to explore the biomechanical factors that cause the snatch failure.

The third research question of this study: Injury is an important factor that plagues athletes' careers. Patella tendinopathy is currently widespread in my athletes, seriously affecting training and competition. There is no consensus on what is the most beneficial treatment strategy for patellar tendinopathy based on the current literatures. Conservative treatments have been recommended as the initial treatments of option for chronic patellar tendinopathy, but the results of many conservative treatments were irregular and inconsistent, and the symptoms frequently recurred. Numerous studies to evaluate the effectiveness of ESWT for patellar tendinopathy in patients who had not responded successfully to conservative treatments. However, the conclusion of most studies is that ESWT was positively contributed to the improvement of pain symptomatology and function. High-frequency ultrasound has a higher resolution for observing soft tissue and can measure subtle variations in diseased tissues. The ultrasonographic changes of patellar tendon tissues can be considered as essential evidence for assessing the effectiveness of ESWT for patellar tendinopathy that should be investigated.

The third objective of this study: To observe the ultrasonic image changes of ESWT

for patellar tendinopathy from the aspect of repairing the patellar tendon tissues, to study the mechanism of ESWT for patellar tendinopathy based on morphosis, and to discuss the value of musculoskeletal ultrasound in assessing the effectiveness of ESWT for patellar tendinopathy.

Therefore, three parts included in my thesis. The first part is "**Differences in key techniques of snatch between top-elite and sub-elite lifters**". The sports performance of athletes in the competition is the true reflection of training. Although the literatures have analyzed the kinematics and dynamics indicators of snatch through 2-D or 3-D methods, most of them are training data, not competition data. In the competition, athletes are affected by factors such as venue conditions, psychology, and competitors etc., and their training level is often restricted. In addition, the lack of data regarding the stability of snatch technique raises questions regarding the appropriateness of using the specific assistant exercises for improving the success of the snatch lift. Therefore, the first part of my thesis will use the 3-D video digitization method to compare the spatial-temporal characteristics of barbell, angular kinematics, and stability of snatch technique difference of the heaviest successful snatch lifts in competition between top-elite and sub-elite lifters.

The results of the first part showed that the maximum vertical- and relative vertical height (normalized by athletes' height) of the barbell, the maximal vertical linear velocity and acceleration of the barbell were significantly greater in top-elite lifters ($p<0.05$). In addition, the flexion angles of the knee joint were significantly greater in top-elite lifters during the knee extension phase (*M1*) and the force phase (*M3*) of the snatch lift. Sub-elite lifters showed less flexion and significantly slower angular velocity in knee joint than top-elite lifters during the knee flexion phase (*M2*) ($p<0.05$). The findings of this part demonstrated the differences in technical characteristics between the two levels. (1) Coaches of sub-elite lifters should focus on exercises suitable to the strength characteristics of the *M1* and *M3* of the snatch lift. (2) The flexor muscles of knee joint among the sub-elite lifters should be strengthened and the ability of generating and utilizing elastic energy during the *M2* of the snatch lift should be improved.

The second part in my thesis is "**Failed snatch based on the human & bar combination barycenter**". Success rate is an important factor for good results in snatch competitions, because each lifter only has 3 attempts to lift the barbell. The technical principle of the snatch shows that weightlifters need to follow the three principles of "Near", "Fast" and "Low" during the snatch process. With the application of 3-D technology, "Phases" is an important supplement to the three principles. However, there are few studies to compare technical differences of successful and unsuccessful snatch actions. Furthermore, the results of these studies reported that there are no significant differences in temporal structure and spatial structure between successful and unsuccessful snatch technique. Since the trajectory of the *COG* of barbell will be different of every attempt of each lifter, and there is a certain relationship between the trajectories of the *COG* of barbell and *COG* of body, it is not accurate enough to evaluate the failed snatch from the two aspects alone, and it is difficult to find the direct factors. Therefore, the second part of my thesis used the human & bar combination barycenter to compare and analyze the characteristics of the successful and failed snatch attempts, including the characteristics of "Near", "Fast", "Low", and "Phases", the parameters of the human & bar combination barycenter.

The results of the second part showed that there was no significant difference ($P>0.05$) between the successful and failed snatch attempts in the parameters such as the maximum vertical rising speed of the barbell, the maximum vertical height of the barbell, the maximum descending acceleration of the body and the time duration of each phase, the height of barbell, the angle of the knee joint and the hip joint at the end of each phase. However, there are significant differences in the variation of the human & bar combination barycenter on the *X*-axis (front and back direction, sagittal axis) in the inertial ascent stage *(M4*) and the squat support stage (*M5*) ($P<0.05$). The findings of this part indicated the factors that led to the failed snatch. (1) The direct cause of the failure of snatch is that the displacement of human & bar combination barycenter on the *X*-axis is not enough to reach the position for supporting barbell during the inertial ascent stage (*M4*) and the squat support stage (*M5*). The reason is that the strength of reclining at the end of the force phase (*M3*) is insufficient, so it is reminded that

weightlifters who often fall forward in snatch should strengthen reclining exercises. (2) Insufficient flexion of the knee joint during the knee flexion phase (*M2*), which leads to a lower maximum vertical speed of barbell may be an indirect factor leading to the failure of snatch. (3) The cumulative variation of human & bar combination barycenter on the *X*-axis can effectively determine the technical characteristics between the success and failure of elite weightlifters in snatch.

The third part in my thesis is "**Ultrasonic image changes of extracorporeal shockwave therapy for patellar tendinopathy**". Patellar tendinopathy, is a common overuse injury and the prevalence is particularly high in athletes, which can cause pain at the inferior pole of the patella, and is currently widespread in my athletes. Regarding the most beneficial treatment for patella tendinopathy, no consensus has been reached in the literature. Extracorporeal shockwave therapy (ESWT) seems to be an effective treatment for patellar tendinopathy, but the effectiveness of ESWT in repairing patellar tendon need to be ascertained. Therefore, in order to solve the problem of many athletes suffering from patella tendinopathy in my college, the third part of my thesis verified the ultrasound imaging changes of length of patellar tendon, thickness of patellar tendon, hypo-echogenic zones, and calcifications zones caused by the ESWT in the treatment of patella tendinopathy.

The results of the third part showed that ESWT combined with rest appeared to be more effective than rest intervention in repairing patellar tendon length, patellar tendon thickness, hypo-echogenic zones, and calcifications zones. The findings of this part indicated that ultrasound imaging can effectively evaluate the benign changes caused by extracorporeal shock wave therapy for patellar tendinopathy.

Abbreviations

***COG*:** center of gravity

***X*-axis:** Athlete's forward and backward direction, the positive direction is directly behind the lifter

***Y*-axis:** Athlete's left and right direction, the positive direction is on the right side of the lifter

***Z*-axis:** Vertical direction, the positive direction is vertically upward

***M1-M6*:** Phases of snatch lift. Knee extension phase (*M1*), knee flexion phase (*M2*), force phase (*M3*), the inertial ascent stage (*M4*), the squat support stage (*M5*), and the support completion stage (*M6*).

***TD* (s):** Time of duration

***HB* (cm):** Vertical height of barbell

***HBR* (%):** Relative vertical height (normalized by lifters' height) of barbell

***VB* ($m \cdot s^{-1}$):** Vertical linear velocity of barbell

***AB* ($m \cdot s^{-2}$):** Vertical acceleration of barbell

***KA* (degree):** Angle of knee joint

***KAV* ($deg \cdot s^{-1}$):** Angular velocity of knee joint

***HA* (degree):** Angle of hip joint

***HAV* ($deg \cdot s^{-1}$):** Angular velocity of hip joint

***BBCOG-X* (cm):** Displacement between *COG* of barbell and body in the *X*-axis

***BCOG-X* (cm):** Displacement of *COG* of barbell in the *X*-axis

***BCOG-Y* (cm):** Displacement of *COG* of barbell in the *Y*-axis

L_{Hmin} **(m):** the minimum distance between the *COG* of body and barbell during the barbell rising

V_{max} **(m/s):** the maximum vertical rising velocity of the barbell

H_{bmax} **(m):** the maximum vertical height of barbell

a_f **(m/s^2):** the maximum falling acceleration of the *COG* of body

H_{b5} **(m):** the vertical height of *COG* of barbell at the end of *M5*

H_{bd5} **(m):** the vertical height of *COG* of body at the end of *M5*

L_{Hz1} **(m):** the distance between the *COG* of body and barbell on the vertical axis at the end of *M4*

L_{Hz2} **(m):** the distance between the *COG* of body and barbell on the vertical axis at the end of *M5*

H_{bd} **(m)**: the fall distance of the barbell

LH **(m):** the distance from the barbell to the *COG* of the human body

W **(N·m):** the resistance moment of the barbell to the *COG* of body

V_{max0} **(m/s):** the most appropriate initial velocity at the end of *M3*

H **(m):** the optimal height for lifters to squat

X_c**:** *X*-axis coordinates of Human & bar combination barycenter

M_1 **(kg):** the weight of lifter

M_2 **(kg):** the weight of barbell

X_1**:** the position of the *COG* of body on the *X*-axis

X_2**:** the position of the *COG* of barbell on the *X*-axis is X_2

Y_c**:** *Y*-axis coordinates of Human & bar combination barycenter

Y_1**:** the position of the *COG* of body on the *Y*-axis

Y_2**:** the position of the *COG* of barbell on the *Y*-axis is Y_2,

Z_c**:** *Z*-axis coordinates of Human & bar combination barycenter

Z_1**:** the position of the *COG* of body on the *Z*-axis

Z_2: the position of the *COG* of barbell on the *Z*-axis is Z_2

g **(m/s^2):** the acceleration of gravity

Y_{cn} **(cm):** the cumulative variation of the human & bar combination barycenter

ESWT: Extracorporeal shockwave therapy

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1 Introduction

1.1 Research on key techniques of weightlifting

1.1.1 Weightlifting research methods

The biomechanics research methods of weightlifting mainly include dynamics, kinematics, and electromyography. Current research mostly uses a single method to study athletes' skills, and two or three of them are used simultaneously for research. Dynamics and electromyography belong to contact measurement, and kinematics methods have the advantages of non-contact and no hindrance to games, so kinematics methods are the most widely used.

The research methods of weightlifting kinematics are constantly evolving with the development of imaging technology. Most of the initial studies used the photo or video of the weightlifting process to conduct two-dimensional qualitative analysis, mainly by reviewing and observing the image data of the weightlifting technique to understand the influence on the weightlifting performance [1], the processing method is relatively simple, but simple judgments can be made quickly. With the development of imaging technology and the emergence of three-dimensional motion analysis technology, the progress from qualitative analysis to quantitative analysis has been realized. In order to better calculate the kinematic parameters, three-dimensional kinematics analysis is often used. Two (or more) cameras are used to simultaneously capture weightlifting images at an appropriate angle and the calibration frame determined by the internal parameters of the three-dimensional kinematics analysis software. After modeling, image acquisition, calibration and analysis, mechanical parameters such as the position, velocity, acceleration of the barbell can be obtained, as well as the kinematic parameters such as the center of mass of the human body and the position of the center of mass of each part of the human body, speed, acceleration, joint angle, angular velocity, angular acceleration, etc. to conduct research and analysis on the technical actions of snatch. Commonly used software systems include Aijie, SIMI MOTION, etc.[2]–[5]. There are steps that require manual calibration during the operation, and there are certain errors.

The processing cycle is relatively long.

At present, a three-dimensional automatic tracking analysis system with markers added to the research object has been widely used in the world for kinematics research. It is mainly represented by the two series of MOTION and PEAK in the United States. It has the advantages of short cycle and high accuracy[6]–[8]. Before shooting images, mark points are attached to the body and barbell end points as needed. This kind of mark points can be recognized by the system and automatically tracked during calibration, thereby reducing calibration errors and speeding up the calibration. In order to obtain more kinematics and dynamics parameters, the three-dimensional motion analysis system is combined with the force platform and the electromyography instrument are used for the barbell running track. Use new algorithms, force measurement curves, athletes' electromyographic characteristics and other regular features to describe the barbell running trajectory, obtain biomechanical information of athletes' weightlifting techniques, find the dynamics and kinematics characteristics of weightlifting techniques, and analyze the problems of a certain technical link[9].

At present, non-marker motion capture systems such as Simi Shape^{3D} have been used. The system uses new algorithms based on image contour information to capture three-dimensional body motion without using anatomical landmarks. The Simi Shape^{3D} system automatically matches the virtual human model with the subject's image from first frame. The length and width of the model link can be adjusted according to the subject, and then the complete image sequence is automatically tracked, and the movement data (translation and rotation) is obtained. The joint position and rotation can also be extracted from the posture and position of the model. Compared with the traditional method, this research method has simpler operation and higher accuracy, and can measure the position, translation and rotation data of each joint.

In the research of real-time acquisition methods of weightlifting technical parameters, researchers have made many efforts and attempts for more than 20 years. In the 1990s, Chinese researcher Ai Kangwei used a tachometer motor to measure the vertical speed of the barbell. The specific method is to use a rope to pass through a specially designed mechanism, one end is fixed to the two ends of the barbell, and the other end is passed

through the tachometer motor. The change in length of the tachometer motor gives the speed of the barbell. However, the rope has a certain force on the barbell, and has a greater impact on the support balance in training. At the beginning of this century, researchers tried to use three-dimensional acceleration sensors, combined with wireless transmission technology to measure the acceleration of the barbell in real time. However, the barbell plate and the barbell bar rotate irregularly during the athlete's lift. Therefore, the direction of the data measured by the sensor installed on the barbell cannot be determined, and the measured data cannot reflect the real movement of the barbell. In recent years, it has tried to use ultrasonic ranging sensors to measure the height change of the barbell from the ground in real time, and designed a suspension mechanism, which is hung on the barbell bar, and uses gravity to ensure that the ultrasonic rays are perpendicular to the ground. This can measure the distance from the barbell to the ground under quasi-static conditions. However, in the actual lift, due to the change of the force direction of the barbell, the suspension mechanism will rotate around the barbell, so that the ultrasonic rays cannot be perpendicular to the ground, and it is impossible to measure the distance of barbell to the ground in real time.

It is very difficult, or even impossible, to collect real-time data on the kinematic parameters of the barbell by using existing methods without affecting the training and competition. With the development of artificial intelligence technology, researchers have begun to use computer automatic identification technology to obtain key technical indicators of the human body and barbell to evaluate the pros and cons of weightlifting techniques. In recent years, with the application of deep neural networks in the fields of pose estimation and action recognition, pose estimation has achieved good results in human action recognition and reasoning, and sports video analysis technology based on pose estimation has developed rapidly[10].

At present, high-resolution recording of athletes' competition videos has been achieved, and the real movement data of the athletes are obtained after multi-dimensional decomposition, and then the video analysis algorithm is used to scientifically decompose tiny movements and compare and evaluate the performance of the competition. By comparing the same action images of different athletes, it can

also help athletes find the difference with standard actions, accelerate the promotion of corresponding actions, reduce the repetitiveness of training, and improve the teaching intuitiveness and the feedback speed. In addition, it can also reduce sports injuries caused by irregular movements, and promote the improvement of training and competition (Figure 1).

Ai Kangwei et al. [11]proposed a weightlifting training real-time diagnostic feedback system, based on the Kinect sensor to collect the RGB video and depth data of the weightlifting, and automatically recognize the barbell through the pattern recognition algorithm to evaluate the weightlifting action (Figure 2).

Figure 1 Application of motion recognition technology in weightlifting.

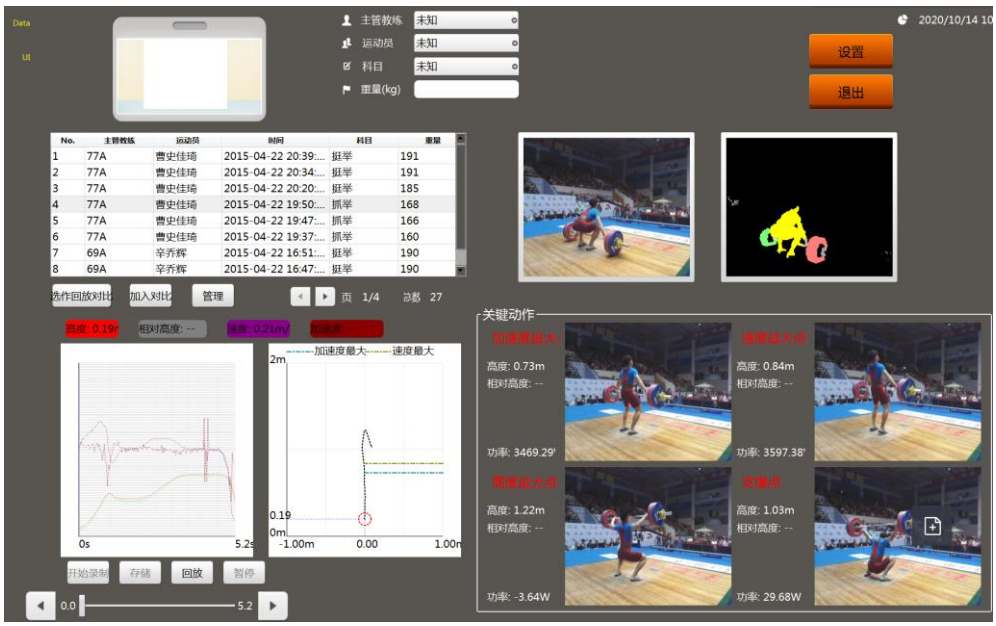

Figure 2 weightlifting training real-time diagnostic feedback system (K. Ai, X. Han, and Z. Bi, 2015).

1.1.2 Snatch technical structure

The snatch technique is clearly divided into six stages in “Competitive Weightlifting”: preparation for lifting the bell, the first step to lift the bell, knee flexion, exert force, squat support, and standing up [12]. Wang Xiangdong’s research pointed out that the main stage of snatch action is from the moment of the barbell leaves the ground until the barbell reaches its highest point, and the main stage action is divided into four stages. The first force stage: from the moment of the barbell is lifted off the ground to the moment of maximum knee extension (the knee joint angle is the largest), it is usually called knee extension and lifting. Transition stage: the knee joint angle starts from the moment of maximum knee extension to the moment of maximum knee flexion (minimum knee joint angle), that is, knee flexion and lifting. The second force stage: the maximum force generation stage, from the moment of maximum knee flexion (the second force start time) to the moment when the barbell rise speed reaches the maximum (the second force end time). Inertial rise phase: from the moment when the barbell rises at maximum speed until the barbell reaches the highest point [13]. Liu Ping’s research pointed out that the previous snatch technical analysis was basically carried out in units of the characteristics of the action stage, which can make the analysis clear, but it is easy to separate the links between the technical procedures. The correlation analysis of technical parameters can find the context of technical characteristics, but it is often between individual variables. From the perspective of factor analysis, he divided the snatch technique structure into five main biomechanical factors according to the contribution rate of eigenvalues: force effect factor, barbell picking adjustment factor, movement trend factor, barbell picking force factor, and force start posture factor [14]. According to Wang Lei's research report, Shi Zhiyong's snatch movement was divided into six characteristic pictures and five stages based on the structural characteristics. The six characteristic pictures are: the bell starts to lift, knees flexion are started, the force starts, the barbell inertia rises to the highest point, the squat to the lowest point, and the lift to the highest point. The five stages are the barbell lifting stage, the knee flexion stage, the force stage, the squat support stage, and the standing up stage [15].

The international literature uniformly divides the snatch technique into the following stages: the preparatory lifting before the barbell lifts off the ground, the first force generation stage (that is, from the moment of the barbell lifts off the ground to the maximum knee extension), transition stage (knee joint angle starts from the moment of maximum knee extension to the maximum knee flexion), the second force generation stage (from the moment of maximum knee flexion to the moment of the maximum barbell speed), squat support stage, and standing up stage. Summarize the literature on the stage division of snatch action, they are only called differently, but their content is essentially the same.

At the preparing stage, it is generally believed that a wide grip distance is used to facilitate rapid arm extension, and a low *COG* of body is beneficial to maintain balance. All joints and muscle groups should be kept tight and fixed. At the moment of lifting the bell, pay special attention to the trunk fixation, shoulder straps tighten, and maintain static tension [16]. The task of knee extension is to lift the barbell to the knee height at a necessary speed while keeping the *COG* of close to the *COG* of body, to prepare for the subsequent knee flexion.

When the knee extension ends, that is, the knee flexion begins. At this moment, the knee joint angle has increased to a larger angle (about 120 degrees), the lower limb strength has been fully utilized, and the upper body anterior inclination is also at a large level. In order to make the barbell continue to rise at a fast speed, it is necessary to actively put the hip extensors and the spine extensor into work, and the upper body pick up quickly to ensure that the barbell continues to rise. In order to make the strong extensor muscle group at the most favorable angle during the critical force phase, so as to better play its role, so when the barbell rises, a knee flexion action appeared.

The force stage is an important stage of snatch technique. The reasonable completion of force-generating movements to raise the barbell to a suitable height is the basis for successful lifting. The barbell height of inertia rise after exerting force is one of the important parameters of the athlete's ability to exert force. The sooner the force action ends, the more time for the athlete to drill down and pick up the bell, but it may reduce the height of the barbell. When the force is over, the barbell can continue to rise by

“swing arms and turning wrists”. At the same time, pulling the barbell up is helpful for the human body to squat quickly.

The maximum speed reached of the barbell when exerting force is an intuitive manifestation of the athlete's force exertion technique, and it can also be used to measure the athlete's potential. The technique of snatch requires that the body should be fully stretched when exerting force, so as to appropriately extend the exertion time of force acting on the barbell, thereby increasing the maximum vertical speed of the barbell [17].

The inertial rise time of the barbell is based on the time from athlete starts to squat to prepare to pick up the barbell. For an excellent weightlifter with better skills, this parameter is very important. If the inertial rise time is too long, it means that athlete is exerting greater force, which will cause energy waste. If the inertial rise time is too short, the athlete will not have enough time to squat and support the bell, which will eventually lead to failed lift [18].

From the moment of the barbell reaches the highest point to the moment of the barbell returns to the lowest point is the squat support stage. In the process of squatting and picking up the bell, the lower limbs should do a concessional squat instead of quickly squatting and waiting for the barbell to fall, which can alleviate the falling speed of barbell [14].

1.1.3 Influencing factors of snatch technique

There are three types of modern competitive weightlifting techniques. One is stretching, such as lifting barbell in snatch and clean and jerk, braking in the pre-squatting of the second part in clean and jerk, standing up after squatting, various stretching exercises, etc. The second is squatting, such as squatting in snatch and clean and jerk, pre-squatting in clean and jerk and various weight-bearing squats exercise. The third is support, such as supporting in snatch and clean and jerk, weight-bearing exercises above the chest and straight arms. Snatch is a movement in which athlete lifts the barbell from the weightlifting platform up to the head with both arms straightened in a fast and continuous motion, with both legs straight, standing on a horizontal line with both feet and maintaining a stable state. Previous studies have shown that the

success of weightlifting attempts depends on factors such as the height of the barbell's ascent, speed, trajectory of the *COG* of body and the barbell, and movement rhythm etc. The acquisition of these factors is determined by the stable balance of human body support, the method of maximum exertion, the coordination of exertion, and the trajectory of the barbell etc. The basic principles of sports biomechanics point out that only with stable and powerful support points can the body's various motion links exert maximum strength and effectively transmit force. For this reason, the principle of "close" is stipulated in weightlifting. The principle of *COG* balance of weightlifting points out that "in all kinds of weightlifting actions such as upward extension and downward flexion squatting, all motion links should be exerted at the same time, and the forward horizontal component and the backward horizontal component of the force should be equal and opposite to obtain the best stable balance" [19].

Liu Weiguo calculated the success and failure rate of the 2004 China Women's Weightlifting Championships. The number of successes accounted for 49.5% of the total, the number of front drops accounted for 28.3%, and the back drops accounted for 20.3%. And also pointed out that the reasons for the front drops are: one is that the *COG* of body is biased forward, and the body's upper and lower coordination is not good. Second, the preparation posture is incorrect, the calf is far away from the barbell, the back is not tightened when the bell is lifted, the knee flexion is not enough, the barbell is not close to the body, and the torso does not maintain proper forward inclination. The third is that when exerting force, there is no upward force, the body is not fully extended, and the arms are thrown out. Fourth, when squatting to support, there is no shoulder lock and the active support.

The reasons for the back drops are: First, the route of the bell is incorrect. Because the body is stretched too early when lifting the barbell, the body does not form a certain inclination angle, it causes the arms to swing with the shoulder as the axis when exerting force, which lead to the barbell to arc upward and swing excessively. There are also the fact that the barbell is too far away from the body, and the barbell deliberately collides with the body when exerting force, which causes the barbell back drop due to the inertial, instead of insufficient squatting support. Due to insufficient front pressure of the calf

during squatting support (poor ankle ligaments), the shoulder position is high, so that the *COG* of body is at the rear, which destroys the stability of the squat support and causes the center of gravity to shift back and cause the barbell to fall behind. The second is insufficient support force. Because the arm and shoulder strap muscles are not strong enough to support the barbell, the barbell falls behind, especially for lifters with poor flexibility of the shoulder strap muscles[1].

Wang Mingxuan's research shows that snatch failures are common after the exertion is over. When the barbell has the same ascent speed and height, sometimes it succeeds and sometimes fails. From the kinematics point of view, many failures are because the maximum vertical distance between the *COG* of barbell and body is not enough to from a favorable support posture[20]. Yu Zhongyou analyzed the stability of the barbell supporting and pointed out that there is no obvious difference between high-level athletes and low-level athletes in the preparation posture and barbell rising phase. However, there are obvious differences in the support phase. High-level athletes are generally able to maintain the barbell within or slightly beyond the support surface, while low-level athletes are significantly beyond the support surface during the support phase. In the preparatory posture and lifting phase, the barbell's center of gravity generally exceeds the support surface in front. This is mainly related to the lifting posture adopted by the athletes. Some athletes have a situation where the barbell's center of gravity slightly exceeds the support surface during the preparation posture. However, the barbell is generally pulled back into the supporting surface during the lifting phase. But if the value is too large, it will inevitably increase the arm of force of the barbell, which will increase the demand for muscle strength under the same weight, resulting in waste of energy consumption. From the experimental results, the barbell's center of gravity beyond the support surface mainly occurs in the squat support stage, which is the most dangerous stage, because the athlete is in the squat support state at this moment and cannot move the footsteps, and can only twist the limbs to control the barbell. If the adjustment is not timely, it will inevitably cause the barbell to fall forward or backward. In the process of standing up, there may also be situations where the center of gravity of the barbell exceeds the supporting surface due to shaking. At this moment,

since it can be adjusted by moving the footsteps, the risk is relatively small. But if there is a big shaking, it will also cause the danger of barbell falling [21].

1.1.4 Snatch key technical parameters

Ray G. Burdit of the University of Pennsylvania [22] comparatively studied the snatch techniques of 10 world-level weightlifters and 26 college level athletes, and showed that world-level athletes lift the barbell at a lower relative height than ordinary athletes, and the average relative height of world-level athletes who lift the barbell is 0.62±0.05 times their height. And college level lifters are 0.69±0.05 times their height. Chinese Wang Mingxuan [20] compared the data of two failures and one success of the 145kg attempts in snatch through stereo camera method from the perspective of sports biomechanics, and found that the barbell's center of gravity of the three attempts all reached the same maximum height. However, the relative vertical height between the *COG* of barbell and human body is different. During the failed attempt, the athlete did not get enough vertical support space. Therefore, the maximum support force cannot be exerted under extreme load conditions, resulting in failure. For this lifter, the relative vertical height is 41.02%, less than this value, the snatch cannot be successful.

J. Cmrhammer's research pointed out that an important criterion for measuring the quality of technical actions is whether the vertical speed of the barbell can always maintain an upward trend during the entire lifting process[23]. There are two types of speed-time curves for the vertical speed of the barbell's center of gravity during the snatch. One type is that the vertical speed curve has two speed peaks on the *X*-axis, in other words, the barbell vertical speed decreases during the transition phase. Another type of vertical speed curve has only one speed peak on the *X*-axis, that is, the vertical speed always maintains an upward trend in the transition phase, without any decline. The barbell’s vertical speed-time curve is mostly the latter of high-level athletes in the snatch process, and there is rarely a significant decline. In other words, elite athletes can still maintain the vertical speed increase in the transition phase. Therefore, many people regard whether the vertical speed of the barbell always maintains an upward trend during the entire lifting process as one of the criteria to measure the quality of snatch technique [24]. Wang Xiangdong et al. conducted a study on the snatch

technique of four outstanding female weightlifters in China by means of three-dimensional analysis and showed that the vertical speed of the barbell center of gravity increases the fastest from the start of the second force to the end of the second force. And the vertical speed of the barbell center of gravity, the angle of the knee joint and hip joint increase simultaneously[13]. Zhang Guimin et al. used a combination of dynamic testing and camera analysis to diagnose and evaluate the technical movements of 9 Chinese national men's weightlifting team. The research results showed that the barbell produces two vertical accelerations during the lifting phase, and the percentages of the two accelerations to the maximum speed are 43.5% and 58.8%, respectively. After reaching the maximum knee extension, begin to flex and pull the barbell close to the body. Zhang Guozheng's maximum strength is 252kg (deducting body weight), the maximum barbell speed is 1.87m/s, and the maximum vertical height of the barbell is 97cm. Zhan Xugang's maximum strength is 321kg (deducting body weight), and the maximum barbell speed is 1.82m/s. Zhang Guozheng raised the bell too high and caused the bell to fall back 43cm, and the vertical pressure of the bell reached 417kg. Both Zhang Guozheng's body weight and barbell weight are smaller than Zhan Xugang, but his drop force value exceeds Zhan Xugang. Zhan Xugang's barbell fall distance is 34cm, which is more reasonable [9].

Ai Kangwei [3] used biomechanical research methods to compare the snatch and squat of Chinese high-level female weightlifters in kinematics and compare the characteristics of strength. In addition, they used inverse dynamics to analyze the joint moments of the two technical movements. The research results showed that the maximum torque of the hip joint for snatch is negatively correlated with the angle of the hip joint at this moment (-0.782, n=12). For squat, the maximum moment of the hip joint is positively correlated with the barbell weight being lifted (0.908, n=11). Zhang Guimin et al. also pointed out that if the vertical height of the barbell is large, it is likely to cause the barbell's falling distance and descent speed to be too large, coupled with its insufficient relieving cushioning, eventually lead to excessive drop force and cause action failure [9].

Zhang Guimin's research shows that most athletes in the squat and bell support stage

have backward jumping movements, which are compensatory movements to maintain the support balance. But jumping should be controlled within a reasonable range to reduce the difficulty of supporting the barbell, and pointed out that reasonable jumping technique and distance are important aspects to improve the success rate of snatch supporting [9]. Liu Ping conducted a research on the power of snatch movement and found that jumping is a key factor on the success or failure of supporting, and it is highly related to the lateral movement of the barbell and the success or failure of supporting the bell. The forward movement of the barbell when knees are bent and the backward movement of the barbell when exerting force are the main factors that determine the jump distance. It is not advisable to lift the bell and accelerate too much during the knee-bending process. The barbell speed at the beginning of the force phase is not highly correlated with the maximum barbell speed, and the barbell height at the beginning of the force phase is not highly correlated with the maximum barbell height, accelerating the barbell too early will destroy the overall rhythm of the action [14].

Wang Xiangdong's research found that the lifting of the barbell in the knee extension phase is mainly accomplished by kicking and knee extension. The premature opening of the hip joint to participate in the lifting is the main factor leading to the failure. The earlier the hip joint is opened, the greater the value of the time ratio, bell rising height ratio and work ratio at this stage. The big proportion of parameters during the knee flexion phase is reflected in the technical movements of fully extending the knee and actively extending the hip. On the contrary, the knee extension is insufficient, and the extension of the hip joint is limited. In the force phase, the barbell lifting is mainly accomplished by simultaneously extending the knees and hips. The explosive force can be fully reflected in this stage. It is manifested in the parameters that the time ratio is small and the work ratio is large [25].

1.1.5 The trajectories of center of gravity of barbell, center of gravity of body, and the human & bar combination barycenter

There are mainly three modes of snatch barbell center of gravity trajectory for elite athletes (Figure 3) [26], [27], but there are still disputes about the pros and cons of the three modes. If the starting joint torque is used as the criterion, then C is the best model.

If the total energy consumption is used as the criterion, it is difficult to evaluate which of the three types is the best [26], [27]. In the snatch process, the rapid extension of the knee and hip joints causes the body to lean back. When the barbell moves, there will be an offset in the *X*-axis direction, and the trajectory shows an “S” shape. This is considered to be the best snatch technique and good barbell trajectory [18]. This offset is considered to be the smaller the better for the vertical rise of the barbell. In the snatch movement of elite male athletes, the maximum horizontal displacement of the barbell corresponding to the vertical reference line of the starting position is 6.29cm on average from the knee-lifting stage to the stage of force exertion [28], [29]. Although this offset will reduce the force of the vertical axis, it is inevitable, because a moderate offset is conducive to taking advantage of the principle of human leveraging. Therefore, during the ascent of the barbell, the barbell should be as close to the body as possible, reflecting the characteristics of “near” [30].

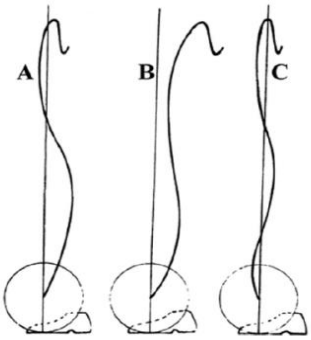

Figure 3 Three barbell trajectory models in snatch (S. L. Nejadian, M. Rostami, and A. Naghash, 2010).

John Garhammer et al. proposed the best trajectory of the barbell's center of gravity for the snatch technique. The movement of the barbell's center of gravity presents an obvious “S”-shaped trajectory due to a moderate deviation from the vertical reference line (the vertical line that passes through the barbell's center of gravity before the barbell is lifted) at each stage. In theory, the smaller the offset, the closer the barbell to the vertical reference line, the more beneficial it is for the barbell to rise. However, due to the technical structure of the snatch, the barbell cannot move linearly along the vertical axis. Therefore, the appropriate deviation in each stage is the inevitable result of the coordinated movement of people and the barbell [23].

Liu Zongyou compared the deviation of the barbell center of gravity and the body center of gravity in the forward and backward directions of the famous Russian weightlifter Chernomyrdin and Chinese athletes in the force phase. The results of the study found that the trajectory of the center of gravity of barbell of Chernomyrdin passed the trajectory of the center of gravity of the body, and the center of gravity of the barbell runs upwards almost close to the center of gravity of body, showing the characteristics of "near" in force phase[31].

Wolfgang Baumann et al. studied the barbell trajectory of the athletes in the 1985 World Championships and found that the barbell trajectory of all athletes did not cross the vertical reference line, but showed that the barbell moved to the back of the body, which eventually caused the athletes to jump back after exerting force, and this is considered to be a manifestation of unstable technique in snatch[26]. Shan Xinhai et al. studied Cui Wenhua's successful snatch technique of 200.5kg exceeding the world record and found that the barbell's center of gravity trajectory crosses the center of gravity trajectory of body in the force phase [32].

The technical principle of the snatch shows that weightlifters need to follow the three principles of "Near", "Fast" and "Low" during the snatch process[33], [34]. "Near" means that the barbell is required to be as close to the body as possible during the lifting process. "Fast" means that pulling the barbell and exert force should be fast. "Low" refers to requiring lifters to reduce the *COG* of body at the fastest speed to facilitate the support to the barbell. Previous research reported that the a_f of elite lifters is greater than the acceleration of gravity g[30].

Initial biomechanical studies on snatch were mainly 2-D small sample subjects. Since 1988, 3-D kinematical researches have begun to appear[34]. With the application of 3-D technology, the parameters which were used to determine the three principles are more diverse and precise. The maximum height of the barbell (H_{bmax}) and the fall distance of the barbell (H_{bd}) are the key parameters to evaluate the support completion phase[35], [36]. The trajectory of *COG* of barbell and body are used as an over analysis of snatch technical characteristics[37]–[39]. Spatial-temporal characteristics of barbell, angle of knee joint, angle of hip joint, angle of ankle joint are parameters for evaluating

the overall structure of the snatch after the division of snatch movement[18], [25]. Phases of snatch movement reveal that the snatch technique must not only conform to the mechanics principle, but also adapt to the body structure and physiological characteristics. “Phases” of snatch is an important supplement to the three principles. In recent years, there have many studies in China on the technical characteristics of elite weightlifters in terms of snatch structure evaluation, *COG* of barbell, and *COG* of human body. Xiangdong Wang, et al. and Jianying Li, et al. used 3-D kinematics method to analyze the time structure, the barbell space structure changes and ratios, and joints angle characteristics of different phases of Chinese female elite weightlifters[18], [25]. Jie Yang et al. and Erbil Harbili compared the technical differences between male and female lifters in a series parameters such as time structure, barbell spatial structure, work ratio, and joints angle[40], [41]. Ikeda et al. and Musser et al. analyzed the technical differences among different categories[42], [43]. However, there are few studies to compare technical differences of successful and unsuccessful snatch actions. Gourgoulis et al. and Zhiyuan Bi et al. reported that there are no significant differences in temporal structure and spatial structure between successful and unsuccessful snatch technique of elite lifters. Only the acceleration of vector direction was different, which indicated that it may be related to the stability of lifters’ snatch process[44], [45].

Previous study reported that the failed snatch of most elite lifters occurred during the support completion phase[20]. Therefore, it is speculated that the main reason for failure of forward or backward is that the relative position of the *COG* of barbell and body on the sagittal plan exceeds the lifters’ control limit. Since the trajectory of the *COG* of barbell will be different of every attempt of each lifter, and there is a certain relationship between the trajectories of the *COG* of barbell and body, Therefore, it is difficult to find the difference between successful and unsuccessful attempts only from the trajectory of the barbell's center of gravity and the trajectory of the human's center of gravity. In this case, the human & bar combination barycenter may be a good choice The concept of human & bar combination barycenter was first coined by Yunde Wang in 1984[46]. However, due to the technical limitations, the characteristics and the roles of human & bar combination barycenter were not explained at that time.

1.2 Rehabilitation and treatment of sports injuries

1.2.1 General situation of research on sports injuries

With the development of sports, the intensity of sports training continues to increase. Although it can improve the physical fitness of athletes in a limited time, it is easy to be affected by various factors during sports training, which may cause sudden injury or recurrence of old injury. Sports injuries are unavoidable in people's exercise. Both professional athletes and amateurs may have different types of sports injuries. Injuries are extremely common in competitive sports, which can cause athletes to be unable to participate in normal training and competition, hinder the improvement of performance, shorten sports life, and even cause lifelong disability or death in severe cases.

In sports training, once an athlete suffers injury, the injury needs to be treated in time to ensure that it can be fully recovered, otherwise it will leave the athlete with injury for long time. In the case of athletes with injuries, continuing high-intensity training is likely to occur injury again. Different training items may cause injuries to different parts of athlete's body. Repetitive high-intensity training for sports events is prone to muscle strain. Excessive training load and unreasonable training methods may cause acute injuries.

Wang [47] surveyed 1,000 high school students (809 boys and 191 girls) who regularly participate in sports training through a questionnaire survey. The results of the study found that only 59 (6.24%) had never been injured in training. The remaining students have experienced varying degrees of injury. The average number of injuries for girls was 3.87±1.02, the average number of injuries for boys was 2.46±0.79, and the number of injuries for girls was significantly higher than that for boys. The sports items in descending order of the number of injuries are: track and field, basketball, football, gymnastics, volleyball, table tennis, martial arts, etc. The main types of injuries for boys are abrasions, dislocations, and muscle strains, while the main types of injuries for girls are joint sprains, dislocations, and abrasions.

Zhong et al. [48] analyzed the causes of sports injuries of amateur sports enthusiasts and professional sports athletes. The study pointed out that the external factors of

amateur sports injuries mainly include inadequate preparation activities, weather and venues, imperfect sports facilities, rough movements, unscientific training, and violates the rules, etc. The internal reasons include inadequate movement skills, poor physical and mental state, clothing that does not meet the requirements, physical and anatomical weakness of the body, lack of knowledge of sports injuries, and excessive difficulty in movement. The study also pointed out that among professional sports athletes, fatigue, training and competition arrangements, and rough fouls are important causes of sports injuries, and there are relatively more acute injuries.

Liu Hongwei et al. [49] conducted a study on the injuries of athletes in winter sports. The study collected data on 6,370 registered athletes for the 2010, 2014 Winter Olympics and 2012 Winter Youth Olympics. The study recorded 789 sports injuries, with an injury rate of 123.9 per 1,000 athletes, and an average of 11% of athletes were injured at least once. The study also systematically analyzed information such as the number of people injured in different items, the location, the type and severity of the injuries.

In weightlifting competitions and training, injuries have always plagued the athletes, directly affecting the athlete's technical and tactical application and performance. Xie Yong et al. systematically investigated the injuries of athletes in competitive weightlifting schools. The results of the study showed that muscle strains and sprains were the most common types of injuries, and the injuries mainly occurred in the upper and lower limbs (46.38% and 32.87%, respectively). Ligament injuries accounted for the highest proportion of tissue injuries (34.78%), followed by muscle injuries, which accounted for 30.43%. The study also pointed out that the main reasons for the injury were excessive relaxation of thoughts, insufficient preparation activities, insufficient physical training level, degeneration of technical movements, excessive exercise load, etc. [50].

Liang Shubo et al. have studied the characteristics of weightlifters' injuries through two years of tracking weightlifting training, and analyzed the causes of injuries. The results of the study showed that chronic injuries accounted for 73.7% and acute injuries accounted for 26.3%. Patellar tendinitis injuries accounted for the highest percentage

(14.7%), followed by lumbar muscle strain (10.5%), lumbar muscle fasciitis (10.5%), and rotator cuff injury (6.41%). The study also pointed out that excessive contraction of the quadriceps muscles when athletes do squatting can cause patellar tendinitis damage, and multiple squeezing of the patella can cause cartilage damage. When the athlete steps up or forward, the knee joint shakes due to insufficient support strength, which can cause knee joint meniscus injury. The main causes of injury are insufficient preparation, technical errors, irregular technical movements, poor local strength, excessive training intensity, excessive fatigue, etc. [51].

1.2.2 General situation of research on patella tendinopathy

Patella tendinopathy is a common chronic injury of the knee joint. It often occurs in jumping-based sports, such as football, basketball, volleyball, track and field, military training, etc., and also common in load-intensity training programs, such as weightlifting [52]–[54]. The clinical manifestations of patella tendinopathy are anterior knee pain, jumping pain, half-squatting pain, up and down stairs pain, knee weakness and other symptoms. The pain is often located at the proximal end of the patella tendon near the patella tip and the point below the patella tendon [53]. Patella tendinopathy often accompanies the athlete's entire sports career. In severe cases, it affects sports performance and even terminates sports career early [55]. At present, the treatment of patella tendinopathy is still a difficult problem. It is easy to relapse and difficult to be treated thoroughly. The existing conservative treatments and surgical treatments have uncertain effects and lack of strong evidence to support [54], [56], [57].

In recent years, with the development of competitive sports and public fitness, patella tendinopathy is not only found in professional athletes, but also in amateur athletes and sports enthusiasts. Ren Yuheng et al. conducted an epidemiological survey on the injury of elite athletes in China, and the results showed that patella tendinopathy accounted for 3.57% of the total number of injuries [58]. The research results of Lian OB et al. showed that the incidence of patella tendinopathy in professional athletes was 14.2%, and there were significant differences in the incidence of different sports. The incidence was higher in jumping events, such as football, basketball, volleyball, tennis, track and field, etc. [59]. Research by H. Vander et al. [60] showed that the incidence of

professional volleyball players and basketball players was 45% and 32%, respectively. The incidence of amateur basketball players was 11%, and the incidence of men was higher than that of women (13.5% VS 5.6%). In addition, J. Zwerver et al. [61] conducted an epidemiological study of patella tendinopathy in amateur athletes and showed that the incidence of patella tendinopathy ranges from 2.5% to 14.4%. Patella tendinopathy has obvious characteristics of events. In addition to jumping events, cycling, climbing, running and other sports characterized by repeated knee flexion and extension are also common.

The patella tendon is located in the inferior anterior of knee joint and can be seen as a continuation of the quadriceps tendon. It starts from the lower edge of the patella and ends at the tibial tubercle. The length of patella tendon is about 4-5 cm, the width is about 3 cm, and the proximal thickness is about 3 mm, the distal thickness is about 5 mm [62], [63]. Patella tendon is mainly composed of tendon cells and collagen fibers secreted by tendon cells. The collagen fibers are arranged in parallel. When there is no load, the collagen fibers have a wavy structure and can be straightened under load, which has a force transmission and buffering effect. The tendon has greater strength and certain elasticity, can withstand 50-100N/mm^2 tension, and can be elongated by 4% of the total length without breaking [64].

The main function of the patella tendon is to transmit power, cushion braking and stabilize the knee joint. The patella tendon can be regarded as a continuation of the quadriceps muscle from the structural point of view. It mainly acts as a force transmission function [53]. It can transmit the force generated by the contraction of the quadriceps muscle to the tibia, and drive the calf movement through leverage to complete the knee extension. The patella tendon is the key to the function of the quadriceps, and it is also the weak point of the power chain and the most vulnerable part. In sports training, due to the over-emphasis on quadriceps strength training, the quadriceps muscles do eccentric contraction during braking, resulting in a strong pulling force. When the patella tendon is excessively stretched, it is easy to cause patella tendon damage, which is also an important cause of patella tendinopathy. The collagen fibers of the patella tendon are arranged in a wave shape when there is no load, and

have a certain degree of elasticity, which can be moderately elongated, and can play a mechanical buffer role during braking [53]. There is a certain limit to the lengthening of the patella tendon. The results of previous studies have shown [53], [64] that the patella tendon can be elongated by 4% without damage. If this limit is exceeded, the patella tendon will be damaged or even ruptured. If the quadriceps muscle is not flexible enough, the elastic cushioning effect will be weakened, and the patella tendon will inevitably cause excessive cushioning compensation during the braking process, and the patella tendon will be passively elongated beyond the bearing limit, causing damage to the patella tendon. The patella tendon is located in the inferior anterior of knee joint and plays a role in stabilizing and protecting the knee joint. In the case of weak ligaments around the knee joint, insufficient strength of the stabilizing muscle group, or imbalance of muscle strength, the knee joint will be unstable. To maintain the stability of the knee joint, it will inevitably increase the load of the patella tendon, overcompensate, and resulting in the patella tendon damage [65]–[68].

The patella tendon is an elastic tissue, which shows a typical stress-strain curve. Within a certain range of mechanical traction, the patella tendon will compensate and adapt. Appropriate mechanical stimulation is beneficial to the repair and remodeling of the patella tendon [68]–[70]. The traction resistance of the patella tendon can reach 4.5-6kp/mm^2, which almost exceeds the traction resistance of some metals such as aluminum [53]. When the patella tendon is passively elongated by 2%, the wavy structure of the collagen fiber will disappear and lose its elastic cushioning capacity. When it exceeds 5%, the collagen fiber will be completely straightened and lose its strain characteristics. If it is pulled further, it will break [64]. The stress of the patella tendon mainly comes from the tension generated by the contraction of the quadriceps. Excessive strength of the quadriceps, or decreased flexibility of the quadriceps, will lead to increased quadriceps tension and increased stress on the patella tendon. Increased stress on the patella tendon will cause excessive tension on the patella tendon, causing accumulating of minor injuries. On the other hand, long-term excessive traction of the patella tendon will cause the elasticity of the patella tendon to decrease, which is not conducive to the repair of the patella tendon injury [71]. In addition, the long-term

excessive traction of the patella tendon will also cause the elasticity of the patella tendon to decrease, fail to retract effectively, and induce patella tendinopathy [65].

A study by Hua yinghui [65] found that the imbalance of the medial femoris and lateral femoris muscles can cause the patella to shift and cause patella tendinopathy. Vander et al. [72] believed that the flexibility of quadriceps and hamstrings is related to the pathogenesis of patella tendinopathy. In the process of emergency braking, the quadriceps muscles are elongated by eccentric contraction, which acts as a buffer for braking and can reduce the load of the patella tendon. If the quadriceps muscle is not tough enough, it cannot be fully elongated during eccentric contraction, and the elastic buffering effect is weakened. During the braking process, it will inevitably lead to excessive compensation of the patella tendon, causing patella tendon damage [68]. The hamstrings and quadriceps constitute the mechanical balance of the front and back of the knee joint. If the hamstrings are excessively tense, spasm, and less tough, the knee extension resistance will inevitably increase during braking, which will increase the load of the patella tendon. In short, during exercise, the other links of the entire kinematic chain are not flexible enough, which will lead to excessive compensation of the knee joint, causing patella tendinopathy.

Patella tendinopathy is more common in running and jumping events. This type of events have the characteristics of fast speed and strong explosive force. During exercise, it needs to stop and brake suddenly. The patella tendon bears a large load and is overused for a long time without sufficient time for repair. It leads to the accumulation of subtle damage to the patella tendon, which is an important cause of patella tendinopathy [54], [71].

Regarding the pathological nature of patella tendinopathy, there are two different views [54], [73]. The first view is that patella tendinopathy is an inflammatory disease. The second view is that patella tendinopathy is a degenerative disease. At present, most scholars tend to think that patella tendinopathy is an overuse injury, and the pathological nature is degenerative changes [54], [73], [74]. The location of patella tendinopathy is mostly under the tip of the patella, followed by the lower end of the patella tendon, and the middle part of the patella tendon has relatively less incidence [75].

The pathogenesis of patella tendinopathy is not yet completely clear. Under normal circumstances, the patella tendon is in a dynamic balance between injury and repair, when the damage is equal to or less than repair, it will not cause patella tendinopathy. Only when the damage is greater than repair, and the accumulation of minor damages, will it lead to degenerative changes in the patella tendon, and eventually lead to patella tendinopathy. When the amount and strength of the tendon exceeds a certain limit, and there is not enough time to repair it, tendon cells will become necrotic due to excessive stress [54], [76]. When the tension of the patella tendon is less than 6% of the maximum tension, the patella tendon will undergo physiological adaptation. If it exceeds 8%, it may break, and if it is between 6%-8%, it will cause damage and cause pain in the patella tendon [77]. The study by Cook et al. [78] showed that the number of repetitions is an important factor in the occurrence of patella tendon overuse injury. The number of training sessions per week is closely related to the incidence of patella tendinopathy. If the number of training times per week exceeds 3 times, patella tendinopathy is more likely to occur. The large amount of training is an important reason for the higher incidence of patella tendinopathy in professional athletes than amateur athletes.

Tendons have the ability to repair themselves, which is the human body's instinct. Tendon injury is mainly manifested as collagen damage or even rupture. Tendon cells secrete collagen to repair the injury. This repair method is called intratendon repair [79], which is an ideal repair method, and the result does not affect the strength of the tendon. If the tendon cells are necrotic and cannot secrete enough collagen for repair, it will lead to the proliferation of the connective tissue. This repair method is called extratendon repair [79], and the result will affect the strength of the tendon. The repair of tendons generally goes through three stages [53]. The first is the inflammatory period, which is characterized by a short period of time. The second is the proliferation period, which is characterized by lasting for several weeks. The last is the remodeling period, which is characterized by lasting for several months.

The cause of patella tendinopathy has always been controversial in academia. Some scholars believe that insufficient quadriceps muscle strength is an important reason of patella tendinopathy [72]. The main reason is that patients with patella tendinopathy

generally have insufficient quadriceps muscle strength and even muscle atrophy. Some scholars also believe that patella tendinopathy is related to excessive quadriceps muscle strength [72]. The basis is that patella tendinopathy often occurs in professional athletes, and professional athletes have stronger quadriceps muscle strength. When the strength of the quadriceps muscle is too strong, the quadriceps muscle contraction excessively pulls the patella tendon during exercise, which easily leads to the injury of the patella tendon. In addition, excessive quadriceps strength will affect the flexibility of the knee joint, weaken the cushioning capacity, and cause an increase in the load of patella tendon.

So, is the patella tendinopathy caused by too strong or too weak quadriceps? In fact, quadriceps atrophy may be caused by patella tendinopathy, and the decrease in muscle strength may be the result of patella tendinopathy, not the cause [80]. Some scholars also believe that if too much emphasis is placed on the strength training of large muscle groups while ignoring the strength training of small muscle groups, especially stable muscle groups, the result will lead to joint instability, excessive compensation of the patella tendon during exercise, and overuse injury [80]. Some scholars believe that the quadriceps muscle undergoes eccentric contraction, and the tensile force of the patella tendon is twice that of the centripetal contraction. This overload is one of the important reasons for the damage of the patella tendon [81]. Some scholars also believe that patella tendinopathy is closely related to the flexibility of the lower limbs [82], [83]. The imbalance of muscle strength of the lower limbs (such as the imbalance of the medial and lateral femoris muscles) can also cause patella tendinopathy [66], [67]. Insufficient muscle coordination and control will cause the patella tendon to bear excessive buffer load in a short time and cause acute injury [78]. Vander et al. [60], [72] found that patella tendinopathy is related to factors such as gender, height, weight, waist-to-hip ratio, leg length, and arch height etc.

In addition, patella tendinopathy has obvious sports differences, which may be related to the characteristics of different sports. Patella tendinopathy mostly occurs in long jump events, such as basketball and volleyball. The number of repetitions of training is an important factor in the onset of overuse injury. Training more than 3 times

a week and large amount of training are important reasons for the onset of patella tendinopathy [78], [84]. Excessive load is also one of the important causes of patella tendinopathy. Excessive training intensity that exceeds the capacity of the patella tendon will lead to acute injury of the patella tendon, and if the acute injury cannot be repaired in time, turning into a chronic injury [81]. Incorrect action patterns can also lead to patella tendinopathy. For example, the internal buckle of the knee joint will cause the patella to shift outward and upward, change the direction of force on the patella tendon, and cause patella tendon injury [85]. The stiffness of the training ground is also related to patella tendinopathy. The ground has weak buffering capacity and large reaction force, which will increase the buffer load of the patella tendon [78], [85].

The course of patella tendinopathy generally lasts for more than three months. Patients with patella tendinopathy will occasionally feel pain and discomfort on the anterior side of the knee in the early stage, which does not affect the movement; In the middle stage, patients will feel pain after exercise; In the middle and late stages, patients will feel pain at the beginning and during exercise, and affect sports performance. In the later stage, patients will feel pain in daily life or even at rest [54], [86].

There are many ways to chech patella tendinopathy. Musculoskeletal ultrasound has high resolution and is more sensitive to pathological changes. Musculoskeletal ultrasound can be used for the diagnosis, location and evaluation of patella tendinopathy [87], [88]. *X*-ray examination can find elongation of the patella tip and calcification in the tendon, which is often used as a differential diagnosis method for patella tendinopathy [53], [80]. MRI has high resolution and can be used to diagnose patella tendinopathy. However, MRI is susceptible to the influence of tissue water, which is easy to cause misdiagnosis, and MRI is expensive.

In the treatment of patella tendinopathy, conservative treatment is mainly used in clinical practice. The commonly used conservative treatment methods are rest, physical therapy, shock wave therapy, eccentric training, PRP injection [54], [56], [89], and acupuncture, massage, and hot compresses etc. in Chinese medicine [53]. At present, there is no recognized optimal treatment plan. Most studies believe that shock wave therapy and eccentric training are more effective, but the long-term effect is not clear

[56]. Chinese scholars have used acupuncture and moxibustion to treat patella tendinopathy and found a higher cure rate [90], [91]. Some scholars also use massage combined with traditional Chinese medicine fumigation and washing to treat patella tendinopathy, and found that massage can reduce the tension of the quadriceps muscle and achieve better therapeutic effects [92], [93]. Many research reports show that rest [54], surgery [54], [64], [80], NSAIDs [94]–[96], Corticosteroids [97], [98], Glyceryl trinitrate (GTN) [99], Platelet-rich plasma (PRP) [100], [101], Ice Application [102] etc. western medicine methods can be used to treat patella tendinopathy. These methods have varying degrees of effect in relieving pain, avoiding inflammation, reducing tissue damage, and removing lesions. There have also been reports of using modern physical therapy, such as extracorporeal shock wave [103], [104], static training [53], concentric training [105], [106], eccentric training etc. [107], [108] to treat patella tendinopathy.

For the evaluation of the treatment effect of patella tendinopathy, most studies use the visual analogue scale (VAS), which mainly evaluates the patient's static knee pain [54], [109]. The pain of patella tendinopathy is related to exercise, and it can be painless or painful under static conditions. Therefore, the use of static VAS assessment alone as an evaluation of the efficacy of patella tendinopathy has limitations. Musculoskeletal ultrasound can measure the changes of tissue morphology before and after treatment, and can be used for the evaluation of patella tendinopathy. It mainly observes the area of the lesion and the morphological changes of patella tendon before and after treatment [75]. MRI can also be used for the evaluation of patella tendinopathy [75]. It can observe the imaging changes of the patella tendon before and after treatment, but MRI is expensive and not universal.

To sum up, patella tendinopathy is an overuse disease, and its pathological nature is degenerative change, which is not easy to cure. Existing treatment measures have certain curative effects to varying degrees, but lack strong evidence to support them. Moreover, for the judgment of curative effect, most studies only focus on relieving symptoms and the improvement of function, and few studies involve changes in patella tendon tissue morphology. Therefore, in the context of the high incidence of patella tendinopathy in competitive sports, it is important to find a treatment that can eliminate

symptoms, improve function, and promote the restoration of patella tendon tissue.

1.2.3 Application of extracorporeal shock wave therapy (ESWT) in treating patella tendinopathy

Extracorporeal shock wave was used to treat fracture healing and chronic soft tissue injury in the early stage, and later evolved into extracorporeal shock wave therapy for the treatment of musculoskeletal diseases. Extracorporeal shock wave therapy has the characteristics of non-invasiveness, small side effects, significant effects, and low cost. In recent years, with the development of radial shock waves, extracorporeal shock wave therapy has become more and more widely used.

According to the patterns of shock wave energy transmission, it can be divided into the following categories. The first is focus shock wave which is often used for the treatment of diseases that require precise positioning (such as delayed union of fractures, etc.) and the treatment of deeper diseases (such as stones, etc.). The second is the flat wave shock wave, which is often used to treat chronic soft tissue injury diseases (such as ulcers) that are shallow and large in size. The third is the horizontal focus shock wave. The application of this category is basically the same as that of the focus shock wave. The fourth is radial shock waves, which are often used to treat chronic soft tissue injuries and cartilage injuries [110].

With the development of shock wave technology, especially the progress of radial shock waves, the application of shock waves in the treatment of tissue diseases has been broadened. Radial shock waves have divergent waves, large area of action, simple operation, fuzzy positioning, less pain during treatment, less side effects, low cost, no need for anesthesia and other favorable factors, so it is easier to be accepted by patients and is useful in the treatment of soft tissue diseases [110].

When shock waves act on biological tissues, compressive stress and tensile stress will be generated at the tissue interface [111]. The instantaneous change of this stress will cause a certain degree of damage to local tissues, which can be used to crush stones and calcified foci [79]. When the shock wave exceeds a certain intensity, the tissue fluid, especially the accumulation of water, can cause a cavitation effect. This can promote the chemical changes of water molecules to generate hydrogen peroxide and a variety

of free radicals. Both hydrogen peroxide and free radicals are oxidants, which can stimulate the repair of local tissue damage. The free radicals produced by the cavitation effect will have a certain destructive effect on the tissues, and can be used to unblock occluded capillaries and improve microcirculation [79]. When the shock wave propagates in the tissue, its vibration energy is continuously absorbed by the tissue and converted into heat energy, thereby increasing the temperature of the local tissue. This temperature increase is beneficial to the treatment of tendons and ligament attachments [79]. When the shock wave acts on the lesion, it can produce a destructive effect, causing new subtle damage to the diseased tissue, thereby activating the repair mechanism [110]. When the shock wave acts on the calcified tissue, it can also crush stones and degrade the calcified tissue. It is often used to treat calcification diseases. When the shock wave acts on the periosteal tissue, it can promote the growth of new bone, and can treat bone nonunion and delayed fracture healing. Shock waves can produce analgesic effects on diseased tissues, but the mechanism is not yet clear. The possible reason is that shock waves can cause strong stimulation to the human body and have an inhibitory effect on nerve endings, thereby relieving pain [79].

Studies have shown that extracorporeal shock waves can be used in clinical applications to treat bone tissue diseases, including non-union, delayed fracture healing and early femoral head necrosis. Shockwave can also be used to treat soft tissue diseases, such as basal fasciitis, calcified supraspinatus tendinitis, etc. Shockwave can also be used to treat patella tendinitis, osteoarthritis, osteonecrosis, etc. [110]. However, bleeding disorders, childhood growth pain, thrombosis, psychiatric patients, tendon ruptures, severe soft tissue injury, arrhythmia, patients with pacemakers, severe hypertension, and pregnancy are contraindications for shock wave therapy.

Commonly used positioning methods for shock wave therapy include pain point positioning, *X*-ray positioning, ultrasound positioning, and surface markers combined with MRI positioning. The pain point location method is mainly based on the patient's complaint of pain points. It needs to be pressed to check the pain points and combined with anatomical landmarks to avoid important nerves and blood vessels. It is often used for soft tissue injury location. *X*-ray positioning uses *X*-ray machines to couple the

treatment point and the shock wave focus point. It is mainly used in the treatment of diseases that require precise positioning, such as the positioning of bone tissue diseases. Ultrasound positioning is to determine the treatment point through ultrasound. Musculoskeletal ultrasound has the characteristics of high resolution, is sensitive to the lesions of the musculoskeletal system, and can be used for the treatment and positioning of bone and soft tissue diseases [79], [110]. MRI positioning is based on MRI combined with body surface markers, and is often used for the treatment of bone and soft tissue diseases.

The energy of extracorporeal shock wave is generally divided into three levels [110], namely low energy level, medium energy level and high energy level. The range of low energy level is 0.06-0.11mJ/mm^2, which is mostly used for the treatment of chronic soft tissue injury diseases, and the range of medium energy level is 0.12-0.25mJ/mm^2, which is mostly used for the treatment of soft tissue diseases, cartilage damage, and shallow bone non-union. The range of high energy level is 0.26-0.39mJ/mm^2, which is mostly used to treat deep nonunion, delayed union of fractures, and femoral head necrosis.

Clinically, shock waves have a wide range of applications in the treatment of musculoskeletal diseases. Viviana et al. [112] reported that the use of shock waves to treat calcified supraspinatus tendinitis can relieve pain and reduce the area of calcification. The study by Ioppolo et al. [113] believes that shockwave treatment of calcified supraspinatus tendinitis can improve the function of shoulder joint, relieve pain, and promote the absorption of calcification. Zhang et al. [114] used radial and focused shock waves to treat plantar fasciitis, and evaluated the treatment effects of the two groups of subjects at 4 and 12 weeks after treatment. The results of the study showed that after 4 weeks of treatment, the treatment effect of the radial group was better than in the focused group, there was no significant difference in efficacy between the two groups after 12 weeks of treatment. Fang et al. [115] used focused shock waves to treat chronic plantar fasciitis in athletes. The results of the study showed that shock waves have a certain therapeutic effect on plantar fasciitis. Michelle et al. [116] conducted a systematic total study on shock wave treatment of Achilles tendinopathy,

and the results showed that the therapeutic effect of shock wave combined with eccentric training is better than that of shock wave treatment alone.

Lei et al. [117] used shock wave to treat professional athletes with patella tendinopathy. The study divided the patients into shock wave therapy group and conventional conservative therapy group. The results of the study showed that shock wave therapy is better than conventional conservative therapy. Xu et al. [118] used shockwave to treat professional athletes with patella tendinopathy. The study divided the patients into shockwave treatment group and other treatment groups. The VAS score was used to compare the treatment effects. The research results showed that the treatment effect of shockwave treatment group is better than other treatment groups. Wang et al. [119] also used randomized controlled trials to verify that shock wave treatment for patella tendinopathy is better than traditional conservative treatment. Leeuwen et al. [120] conducted a systematic review study on shock wave treatment of patella tendinopathy. The study showed that shock wave treatment of patella tendinopathy is effective in relieving pain and improving function, but the systemic treatment plan and mechanism need to be further explored. The research of Koen et al. [54] also believes that shock wave treatment of patella tendinopathy has the effects of analgesia, smashing calcification and promoting tissue regeneration.

Zhang et al. [121], [122] used radial and focused shock waves to treat external humeral epicondylitis and internal humeral epicondylitis, respectively. The VAS score was used to evaluate the treatment effect at 4 and 12 weeks after treatment. The results of the study showed that the therapeutic effect of the radial shock wave group was better than that of the focused shock wave group after 4 weeks of treatment, and there was no significant difference in the treatment effect between the two groups after 12 weeks. Rompe et al. [123] through meta-analysis, believe that shock wave treatment of external humeral epicondylitis has a good effect. Lee et al. [124] used shock wave to treat external humeral epicondylitis and internal humeral epicondylitis. The study divided patients into shock wave treatment group and injection treatment group. The results of the study showed that the treatment effect of injection group was better than shock wave treatment after 2 weeks. After 8 weeks, the treatment effect of the shock wave treatment

group was better than that of the injection group.

Jing et al. [125] used shock waves to treat inflammation of long tendon of biceps muscle. The study divided the patients into ultrasound positioning group and pain positioning group. The results of the study showed that shock waves are effective in treating inflammation of long tendon of biceps muscle. The treatment effect of ultrasound positioning group is better than that of pain positioning group. Dai [126] used shock waves to treat biceps long head tendon tenosynovitis. The study randomly divided the patients into shock wave groups and control groups. The control group used physical therapy such as microwave or ultrasound. The results of the study showed that extracorporeal shock wave is better than microwave and ultrasound in treating biceps long head tenosynovitis.

Alvarez, Vulpiani et al. [127], [128] used shock waves to treat delayed union of fractures. They believed that shock wave treatment of delayed union of fractures has good therapeutic effect and safety. Xing et al. [129] and Vulpiani et al. [130] used shock waves to treat avascular necrosis of the femoral head in adults, and observed the percentage of the volume of the femoral head in the necrotic area after treatment, Harris score, and Ficat pain index. The results of the studies showed that shock waves have a good therapeutic effect in treating avascular necrosis of the femoral head in adults. Zhai et al. [131] used shock waves to treat traumatic avascular necrosis of the talus. The study randomly divided patients into a treatment group and a control group. The results of the study showed that shock waves have a good therapeutic effect in the treatment of traumatic avascular necrosis of the talus. Xing et al. [132] used shock wave combined with ankle arthroscopy to treat talar osteochondral injury. The results of the study stated that shock wave combined with ankle arthroscopy has a good therapeutic effect for the treatment of talar osteochondral injury.

Numerous studies have shown that shock waves have a wide range of applications in soft tissue diseases and bone tissue diseases. At the same time, there are also reports of shock waves to treat other diseases, such as myocardial ischemia [133], diabetic foot [134], skin ulcers [135], muscle spasms [136] and prostatitis [137]. However, the application of shock waves in many diseases is still in the trial and clinical experience

stage, and the exact therapeutic effect and mechanism need to be verified by large-sample clinical randomized controlled trials.

Leeuwen et al. [120] through literature research found that shock wave treatment for patella tendinopathy has definite therapeutic effect, but there are problems such as unspecific operation methods and treatment parameters, small sample size, and short follow-up time. Zwerver et al. [109] confirmed that shock waves are effective in treating patella tendinopathy through controlled trials. The study observed the improvement of pain symptoms and function, but did not study the changes in tissue structure. At present, there are relatively few studies on the changes of the tissue structure of the shock wave treatment of patella tendinopathy. Wang et al. [119] used shock waves to treat chronic patella tendinopathy, and observed changes in the thickness of the patella tendon with ultrasound. The study found that the thickness of the patella tendon on the affected side of the patella tendinopathy became thicker. After shock wave treatment, the thickness of the patella tendon became thinner.

Shockwave treatment of patella tendinopathy has strict requirements on the course of the disease, mainly for the treatment of chronic injuries, which is defined as the course of more than 3 months [138]. Many studies using shock wave to treat chronic patella tendinopathy selected cases with more than 3 months, and it is believed that shock wave treatment is used when conservative treatment is ineffective [109], [119], [139]. At present, regarding the concept of when to use shock wave to treat patella tendinopathy, it is generally believed that as long as it meets the indications of shock wave therapy and excludes contraindications, it can be used [110].

The inclusion criteria of patella tendinopathy in the literature are not uniform. For example, the inclusion criteria of the study by Wang et al. [119] are: patients with a diagnosis of chronic patellar tendinopathy established by medical history and physical examination; Patients who experienced pain of 5.0 or greater on a 0-to-10 visual analog scale while walking up and down stairs; Patients who understood and complied with the nature of the study participation; Patients who were 21 years and older and skeletally matured; Patients who were physically and mentally competent to sign the informed consent form; And patients who were in good general health. The inclusion

criteria used in the study by Henk et al. [86] are as follows: a history of pain in the patellar tendon or its patellar or tibial insertion in connection with training and/or competition; Symptoms for over three months (to exclude acute inflammatory tendon problems and de novo partial ruptures); Age between 18 and 50 (to reduce chances of other osteochondrotic diseases like Sinding-Larsen-Johanson, Osgood-Schlatter and osteoarthrosis); Palpation tenderness of the patellar tendon; And a score below 80 on the VISA-P questionnaire.

The exclusion criteria for patella tendinopathy varies with the research subjects. For example, the exclusion criteria of Wang et al. [119] are: patients who received a cortisone injection within 6 weeks; Patients on immunosuppressant agents and/or corticosteroid within 6 months; Patients with diabetes mellitus, occlusive vascular disease, collagen disease, osteoarthritis or rheumatoid arthritis, coagulopathy, or infection; Patients with radiographic fractures around the knee; Patients with cardiac arrhythmia or cardiac pacemaker; And patients who were pregnant. The exclusion criteria used in the study of Henk et al. [86] are as follows: acute knee or patellar tendon injuries; Chronic joint diseases; Signs or symptoms of other coexisting knee pathology; Contraindications for ESWT (pregnancy, malignancy, coagulopathy); Knee surgery or injection therapy with corticosteroids in the last three months; And daily use of drugs with a putative effect on patellar tendinopathy in the last year (e.g. non-steroid anti-inflammatory drugs), or use of anticoagulants.

Regarding the grouping method of shock wave treatment for patella tendinopathy, Henk et al. [86] used the computerized random number table grouping method, but many studies did not describe the grouping method in detail. The treatment methods used in the control group usually include conventional conservative treatment [119], blank shock wave [120] and massage therapy [140]. Routine conservative treatment includes taking NSAIDs, physical therapy and rehabilitation training. The shape and sound of the blank shock wave are the same as the shock wave, but no shock wave is generated or the energy of the shock wave is much lower than the shock wave treatment group.

Radial shock waves are mostly used for diseases that are shallow and do not require

precise positioning. Most studies use radial shock waves to treat patella tendinopathy and have good clinical treatment effects. However, some studies have suggested that shockwave treatment of patella tendinopathy has no obvious effect on athletes in the season [141]. There are relatively few studies on the treatment of patella tendinopathy with focused shock waves. The research of Wang et al. [119] pointed out that focused shock waves have a good therapeutic effect in the treatment of patella tendinopathy. There are also studies comparing focused shock waves and radial shock waves in the treatment of patella tendinopathy. Zwerver et al. [109] conducted a randomized double-blind experiment to compare and analyze the therapeutic effects of two shock wave types in the treatment of patella tendinopathy. The results of this study suggest that focused shock waves and radial shock waves have different mechanisms of action. Their research in 2014 found that both radial shock waves and focused shock waves have good therapeutic effects in the treatment of patella tendinopathy, and there is no difference between the two types [142].

Appropriate energy is the key to shock wave treatment to treat patella tendinopathy. The choice of energy is often based on the operator's experience and the patient's tolerance. For example, Wang et al. [119] selected 14KV voltage based on previous treatment experience. Van Leeuwen et al. [120] believe that the shock wave energy level can be divided into three levels, the energy parameter of low energy level is less than 0.08mJ/mm^2, the energy parameter of medium energy level is 0.08-0.28mJ/mm^2, and the energy parameter of high energy level is greater than 0.6mJ /mm^2, when using high-energy level to treat patella tendinopathy, severe pain will occur, and local anesthesia is required.

Regarding whether anesthesia is used in the treatment of patella tendinopathy with shock wave, some studies believe that the effect of not using local anesthesia is better than using local anesthesia [143], [144]. Radial shock wave treatment does not require anesthesia in most cases. Common adverse reactions of shock wave treatment are pain, local skin redness or ecchymosis. Serious adverse reactions need to be iced or taken analgesics after treatment, and strenuous exercise should be avoided during treatment [119].

The evaluation methods of the treatment effect of patella tendinopathy mainly include VAS score, VISA score and ultrasound examination. The VAS score is an internationally accepted pain scoring method, and it is also a commonly used method for evaluating the effect of shock wave treatment on patella tendinopathy. Most studies use static scoring, but the characteristics of patella tendinopathy pain are closely related to exercise. It is often painless or mild at rest, so VAS cannot fully reflect the recovery of patella tendinopathy. Using VAS score to assess the recovery of patella tendinopathy should be combined with special sports movement. The VISA score is a special score sheet for jumping knees [145], with good reliability and validity, and can fully reflect the symptoms and functional status of the patient's patella tendon. Musculoskeletal ultrasound has a high resolution and can measure the morphological changes of the patellar ligament, which has great meaning to evaluate the treatment effect [146].

To sum up, extracorporeal shock wave therapy (ESWT) has broad application prospects in the treatment of soft tissue diseases. Many studies have reported shock wave treatment of calcific supraspinatus tendinitis [147], tennis elbow [148], plantar fasciitis [79] and other diseases, and a few studies have reported shock wave treatment of patella Tendinopathy [86], [120]. Most studies evaluate the therapeutic effect of shock wave treatment of patella tendinopathy mainly by observing pain [120], some studies involve the improvement of knee joint function [119], [120], and only a few studies have analyzed the changes in patella tendon tissue morphology [119]. With the development of musculoskeletal ultrasound, observing the morphological changes of the patella tendon and the changes of the lesions through ultrasound imaging has important application value in the diagnosis, location and evaluation of the shock wave treatment of patella tendinopathy.

1.2.4 Application of ultrasound technology in evaluating patella tendinopathy

Musculoskeletal ultrasound has been widely used in the diagnosis and treatment of impingement syndrome of the shoulder, elbow, hand, hip, knee and ankle, tendinopathy, and arthritis. In recent years, ultrasound technology has been further developed, such as elastic ultrasound imaging and ultrasound-guided PRP injection. Eugene et al. [87] conducted a systematic review study on the application of ultrasound in the field of

sports medicine. The results of the study showed that a total of 617 articles were published from 2003 to 2012, of which 151 were musculoskeletal ultrasound. Musculoskeletal ultrasound has become more and more widely used in soft tissue diseases. Musculoskeletal ultrasound is not only a diagnostic tool, but also used for auxiliary treatment and evaluation.

Musculoskeletal ultrasound has a wide range of applications in the musculoskeletal system. Bruno et al. [149] used ultrasound to examine the Achilles tendon of patients. The results of the study showed that musculoskeletal ultrasound can detect abnormal changes in the Achilles tendon, such as partial rupture, postoperative changes, nodules, calcification, and hypoechoic. Gondolph et al. [150] used ultrasound to examine the Achilles tendon of athletes. The study found that 75% of athletes had structural changes in the Achilles tendon, and the structural changes were correlated with clinical symptoms. Ocguder et al. [151] used musculoskeletal ultrasound to examine shoulder joint injuries of basketball, handball, volleyball, and water polo players. The study found that the average thickness of the subacromial sac of athletes with shoulder joint injuries was higher than that of asymptomatic volunteers, and the study concluded musculoskeletal ultrasound is of great significance in the early diagnosis of shoulder joint injuries. Musculoskeletal ultrasound can be used to detect tendon injuries. The main manifestation of acute tendon rupture is the interrupted continuity of the tendon. Real-time ultrasound can find the activity and docking of the stump [152]. Musculoskeletal ultrasound has high resolution, can detect subtle changes in diseased tissues, and is sensitive to calcification. It is better than MRI in some aspects and has been widely used in musculoskeletal diseases.

Musculoskeletal ultrasound is a common method for the examination of patella tendinopathy. The patella tendon is dense and contains a lot of collagen fibers. It is shallow and located between the subcutaneous tissue and adipose tissue. The echo area of the patella tendon is sharply contrasted with other tissues, and the ultrasound image has clear boundaries, which is conducive to the ultrasound examination of the morphological and structural changes of the patella tendon. High-frequency ultrasound has weak penetrating power and high resolution. It can observe the outline and internal

fine structures of the patella tendon, and is suitable for the inspection of the patella tendon [153].

Regarding the method of ultrasound examination of the patella tendon, the American Society of Ultrasound in Medicine (AIUM) and the American College of Radiology (ACR) formulated the musculoskeletal ultrasound guidelines in 2012, which stated that the patient should bend the knee at 30° in the supine position and examine the front of the knee joint. It also shows that the patella tendon and quadriceps tendon need to be scanned longitudinally and laterally [88]. The European Society of Musculoskeletal Radiology (ESSR) developed guidelines for musculoskeletal ultrasound in 2010. The guidelines stipulate that patients should bend their knees at 30° in a supine position and perform longitudinal and transverse scans of the patella tendon [154]. According to the Chinese musculoskeletal ultrasound examination specifications, the patient is in a supine position with knee flexion 30°-45° [155].

The patella tendon can be regarded as a continuation of the quadriceps tendon, starting from the tip of the patella and ending at the tibial tubercle. The length is about 4-5cm, the width is about 3mm, and the distal thickness is about 5mm [62], [63]. The patella tendon is composed of longitudinally arranged collagen fibers, and the patella tendon is uniformly thin line-like medium echo in longitudinal scanning of ultrasound, and the boundary with the surrounding tissue is obvious. Transverse scanning showed homogeneous spot echoes with clear boundaries and oblate. The proximal end of the patella tendon was slightly larger than the distal end. The thickness of the upper end was about 3mm, the thickness of the distal end was about 5mm, the width of the upper end was about 10mm, and the width of the lower end was about 15mm [153].

The abnormal manifestations of the patella tendon by ultrasound examination mainly include the following aspects. First, patients with patella tendinopathy have focal hypoechoic or diffuse hypoechoic areas at the lesion [64]. Hypoechoic is a typical ultrasound image of patella tendinopathy [156]. After tendon injury, tendon cells become degeneration and necrosis, collagen fibers are edema and ruptured, and the intercellular matrix increases. Therefore, patella tendinopathy manifests as hypoechoic changes [157]. Second, color Doppler flow imaging (CDF) is used to detect local blood

flow signals in patients with patella tendinopathy [54]. Third, local swelling will occur in the acute phase of patella tendon injury, and the affected side of chronic patella tendinopathy is significantly thicker than the opposite side [119]. Fourth, ultrasound examination of patients with patella tendinopathy shows calcifications, which are manifested as strong echoes of varying sizes and irregular shapes within the tendon [152]. Fifth, partial tearing of the patella tendon is manifested as swelling of the patella tendon, uneven echoes, and honeycomb-like hypoechoic areas or plaque-like strong echoes. Complete rupture is manifested as the continuity of the patella tendon interruption, the spacing becomes larger, there are dark areas or plaque-like strong echoes in the spacing, and the echo is unevenly enhanced [153]. Sixth, in the later stage of patella tendinopathy, with the increase of matrix, the degeneration of collagen fibers and the repair of scars, tendon thickening will occur [54]. Zhang et al. [158] used musculoskeletal ultrasound to measure the thickness and cross-sectional area of the patella tendon in patients with patella tendinopathy. The study found that the thickness and cross-sectional area of the affected side were significantly higher than those of the healthy side.

The use of musculoskeletal ultrasound to detect patella tendinopathy requires the examiner to be familiar with the anatomical structure of the patella tendon. Both longitudinal and transverse examinations are required, which is conducive to the three-dimensional and accurate positioning of the lesion. Horizontal scanning is helpful to determine the position of the longitudinal scanning probe and reduce errors. During the inspection, the probe must be perpendicular to the tendon, otherwise it is prone to hypoechoic artifacts [153]. When musculoskeletal ultrasound assesses the shape of the lesion, the inspection result is easily affected by the patient's position and degree of cooperation, so it is necessary to describe the inspection precautions to the patient before the inspection.

Patella tendinopathy may occur in the proximal, distal, middle and diffuse injuries. Shi et al. [153] used ultrasound to diagnose 21 patients with patella tendinopathy. The study found that the injury occurred 4 cases at the proximal end, 5 in the middle, 4 at the distal end, and 8 cases of diffuse injury. Among them, there were 5 cases of

contusion and laceration, 13 cases of partial tearing, and 3 cases of complete rupture. Although patella tendinopathy often occurs under the tip of the patella, the pathology of the lower dead point of the patella tendon is also more common, so it is great significance to locate the injury site with the help of ultrasound.

In the literature of using shock waves to treat patella tendinopathy, there are relatively few studies using ultrasound positioning [119], and most studies are based on clinical experience and pain points. Clinically, there are cases where the self-reported pain point does not match the pressing pain point and the ultrasound examination. Therefore, the combination of ultrasound positioning and pain positioning will facilitate the accurate positioning of the lesion, and will make the shock wave treatment more targeted.

Regarding the evaluation of the treatment effect of patella tendinopathy, most studies currently use VAS score and VISA score to observe pain relief and functional improvement. There are relatively few studies using ultrasound to evaluate the changes in tissue structure before and after treatment of patella tendinopathy with shock wave treatment [54]. Wang et al. [119] used focused shock waves to treat patella tendinopathy and observed the thickness of patella tendon with ultrasound. The results of the study showed that the thickness of patella tendon decreased by 6% in the shock wave treatment group and increased by 10% in the control group.

To sum up, the therapeutic evaluation of patella tendinopathy requires a comprehensive evaluation with symptom improvement, functional improvement and morphological changes. Clinically, the combination of ultrasound positioning and pain positioning can improve the pertinence of shock wave therapy. Ultrasound can not only assist in the diagnosis and treatment of patella tendinopathy, but also can be used to study the morphological changes of patella tendon tissue before and after treatment.

1.3 Aims and objectives

Up to now, I have provided scientific research support for Chinese professional athletes preparing for international competitions, such as the Olympics, for more than 10 years, and I am deeply aware of the technical and injury problems that plague athletes' further improvement of performance. In my thesis, based on the existing literatures and work needs, I would like to draw up three questions that that are not yet clear or need to be solved urgently.

The 1st research question:

In the past four Olympic Games (2004, 2008, 2012, and 2016) Chinese male athletes have won the gold medals in the 69-kg class of weightlifting. The 69-kg class in China, which is identified as the category with the greatest depth of lifters from top to bottom. The technique of top-elite athletes represents the best performance, and can be considered as excellent technical model or a reference that should be achieved.

Previous studies of snatch performance focused mainly on the differences in adult female weightlifters, between adult and adolescent males, and between genders. They analyzed the kinematic and kinetic parameters by two or three-dimensional methods. However, the lack of data regarding the stability of snatch technique raises questions regarding the appropriateness of using the specific assistant exercises for improving the success of the snatch lift. Furthermore, no study was found within the literature that compared the snatch performances between top-elite and sub-elite male weightlifters.

Therefore, my 1st objective is:

To highlight the differences of technical characteristics between top-elite and sub-elite male weightlifters, to summarize the technical features of top-elite athletes, and to provide valuable information for numerous lower level lifters and coaches to integrate into training and competition.

The 2nd research question:

In the snatch competition, each athlete only has 3 attempts to lift the barbell, so the success rate is the guarantee for the best results. There are few studies to compare technical differences of successful and unsuccessful snatch actions in literature. The failed snatch attempts of elite lifters often occurred during the six phase, therefore, it is speculated that the main reason for failure of forward or backward is that the relative position of the *COG* of barbell and body on the sagittal plan exceeds the lifters' control limit. Since the trajectory of the *COG* of barbell will be different of every attempt of each lifter, and there is a certain relationship between the trajectories of the *COG* of barbell and *COG* of body, the present study proposes to use the human & bar combination barycenter as the research parameter to find the reason of failed attempts.

Therefore, my 2nd objective is:

To analyzed the three principles of "Near", "Fast", and "Low", the phased principle, and the human & bar combination barycenter, to exposit the differences between successful and unsuccessful characteristics of snatch attempts in competition, and to explore the biomechanical factors that cause the snatch failure.

The 3rd research question:

Injury is an important factor that plagues athletes' careers. Patella tendinopathy is currently widespread in my athletes, seriously affecting training and competition. There is no consensus on what is the most beneficial treatment strategy for patellar tendinopathy based on the current literatures. Conservative treatments have been recommended as the initial treatments of option for chronic patellar tendinopathy, but the results of many conservative treatments were irregular and inconsistent, and the symptoms frequently recurred. Numerous studies to evaluate the effectiveness of ESWT for patellar tendinopathy in patients who had not responded successfully to conservative treatments. However, the conclusion of most studies is that ESWT was positively contributed to the improvement of pain symptomatology and function. High-frequency ultrasound has a higher resolution for observing soft tissue and can measure subtle variations in diseased tissues.

The ultrasonographic changes of patellar tendon tissues can be considered as essential evidence for assessing the effectiveness of ESWT for patellar tendinopathy that should be investigated.

Therefore, my 3rd objective is:

To observe the ultrasonic image changes of ESWT for patellar tendinopathy from the aspect of repairing the patellar tendon tissues, to study the mechanism of ESWT for patellar tendinopathy based on morphosis, and to discuss the value of musculoskeletal ultrasound in assessing the effectiveness of ESWT for patellar tendinopathy.

2 Subjects and Methods

2.1 Differences in key techniques of snatch between top-elite and sub-elite lifters

2.1.1 Subjects

The data were collected during the 2015 men's Chinese National Championship and the 2016 men's Chinese Olympic Trials. The top six place getters at the Olympic were considered to be top-elite athletes in China. These six athletes were members of the Chinese National Weightlifting Team. Between them, they had won three Olympic Games gold medals, two World Championships gold medals, and one Asian Games gold medal. Athletes ranked from second to seventh at the Chinese Championships (second-tier weightlifting event in China) were considered to be sub-elite athletes. The lifter who won the gold medal was eliminated because he was included within the top-elite group. Data on age, body mass, height, and their best result are shown in Table 1. This study was authorized by the Ethics Committee of Zhejiang College of Sports. Before taking part in the study, all subjects were informed of the objectives, experimental procedures and risks associated with this study. All subjects gave consent to participate in this study.

Table 1 The characteristics of top-elite and sub-elite weightlifters (n=6).

Subjects	Age (y)		Body mass (kg)		Height (m)		Best result (kg)	
	Top-Elite	Sub-Elite	Top-Elite	Sub-Elite	Top-Elite	Sub-Elite	Top-Elite	Sub-Elite
1	29	23	68.90	68.50	1.71	1.63	158	151
2	23	21	68.58	68.55	1.69	1.58	157	150
3	27	20	68.92	68.71	1.68	1.65	157	147
4	26	23	68.93	68.47	1.70	1.60	156	145
5	27	20	68.92	68.58	1.68	1.70	155	142
6	26	21	68.71	68.93	1.71	1.66	152	141
Mean	26.33	21.33*	68.83	68.62	1.70	1.64*	155.83	146.00*
(SD)	（1.97）	（1.37）	（0.15）	（0.17）	（0.01）	（0.04）	（2.14）	（4.10）

* Statistically significant difference ($p<0.05$).

2.1.2 Experimental design

According to comparative method, this study was conducted to determine the differences in technical characteristics between top-elite and sub-elite athletes in male weightlifting for the snatch style. The heaviest successful snatch lifts from three attempts for each subject were chosen for analysis. 3D analysis was carried out to investigate the kinematics of the barbell and angular kinematics of the lower limb. The video data were captured under completion conditions. In video parsing, it is common that body joints are hidden by local limbs or are not visible on the side camera. In this case, it is determined by the estimated method. The staff who processed video data is familiar with human anatomy, and they have more than ten years of experiences in using SIMI°Motion7.50 3D analysis software. These facts guarantee the accuracy of the data.

2.1.3 Procedures

In order to determine the kinematic parameters of the barbell and the lower limb, video and a computerized technique were employed. Two cameras (SONY HDR-FX1000 at 50 Hz) were set up in the horizontal plane, approximately 10 meters away from the subjects. The optical axis of each camera formed an angle of 45 degrees with the frontal plane of the subject (Figure 4-a). The position and focal length of the cameras remained unchanged during the whole process of snatch lift. The methodology of our study focused on video recording, conversion of video capture into AVI format and the kinematic variables which were analyzed by SIMI°Motion7.50 3D analysis system (Germany). Before the start of the competition, a PEAK 3D framework was used to calibrate the movement space (Figure 4-b). The spatial coordinates of various points were calculated from the collected video by means of direct linear transformation (DLT) method (Figure 4-c). The raw position-time data were smoothed by a low-pass digital filter with a cut-off frequency of 4 Hz[40], [159].

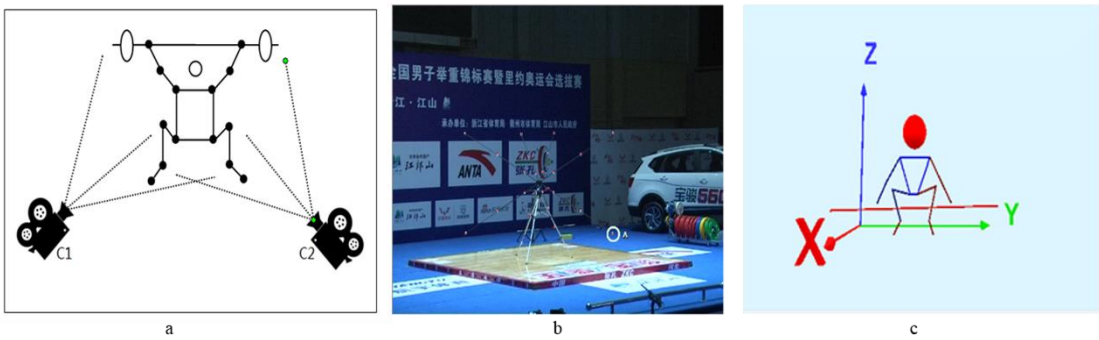

Figure 4 Experimental setup and 3D coordinate system. (a) Cameras set in the competition area. (b) PEAK 3D framework calibrate the movement space. (c) The spatial coordinates of the movement space.

Previous researchers have divided the snatch action into six phases, including the first pull, the transition, the second pull, the turnover under the barbell, the catch phase, and the rising from squat position, based on the changes in the direction of knee angle and the height of the barbell[26], [40], [160]–[162]. The first five phases were considered to be the most important phases of the snatch lift[159], [160], [163], [164]. In the present study, the snatch process (from start position to squat position) was

divided into six phases based on the changes in direction of the knee angle, the vertical velocity of barbell, and the vertical height of barbell, as follows (Figure 5):

1. The knee extension phase (1st phase, *M1*, a-b): from start position to the instant of first maximum knee extension angle;

2. The knee flexion phase (2nd phase, *M2*, b-c): the instant of knee angle from maximum to minimum;

3. The force phase (3rd phase, *M3*, c-d): from the end of *M2* to the maximum vertical rising velocity of barbell;

4. The inertial ascent stage (4th phase, *M4*, d-e): from the end of *M3* to the maximum vertical height of barbell;

5. The squat support stage (5th phase, *M5*, e-f): from the end of *M4* to the maximum vertical falling velocity of barbell;

6. The support completion stage (6th, phase, *M6*, f-g): from the end of *M5* to squat position.

Figure 5 The characteristic pictures at each phase of snatch lift. Each picture represents the beginning and end of each phase.

2.1.4 Definition of variables

In order to acquire the kinematic parameters during the snatch lifts, seventeen key points on the barbell and the body were selected, which were manually digitized using the SIMI°Motion7.50 3D analysis system (Figure 6). These points included the head (midpoint of the line connecting left and right acoustic meatus), left shoulder, right shoulder (think of the upper arm including acromion as a spherical geometry, its center is approximately defined as the shoulder motion center), left elbow, right elbow (distal humerus medial/lateral epicondyle), left wrist, right wrist (horizontal midpoint of styloid process height), left hip, right hip (vertex of greater trochanter), left knee, right knee (femoral medial/lateral epicondyle), left ankle bone, right ankle bone (fibula lateral condyle or medial malleolus), left tiptoe, right tiptoe, left and right endpoints of barbell[165]. *COG* position of body was calculated using Hanavan Body Mathematical Model in the SIMI°Motion7.50 3D analysis software. *COG* position of the barbell was obtained by calculating the geometric center from the coordinates of the two endpoints in the SIMI°Motion7.50 3D analysis software.

The present study focused on the snatch technique from the liftoff to the squat position (*M1-M6*). The choice of parameters were based on theoretical and practical requirements used in training. Our study selected several variables to evaluate the spatial-temporal characteristics of the snatch lift, to analyze kinematic characteristics of the lower body, and to investigate the stability of the snatch technique. The experimental variables show in the abbreviations.

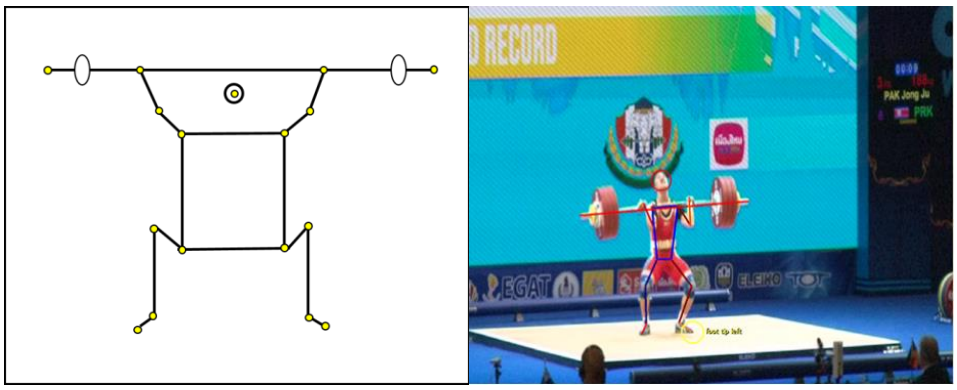

Figure 6 Seventeen key points on the barbell and the body digitized in analysis system.

2.1.5 Statistical analyses

The hypotheses of normal distribution and homogeneity of variance were analyzed via Kolmogorov- Smirnov and Levene's tests, respectively. Age, body mass, height, best result, relative vertical height of the barbell, and vertical acceleration of the barbell were analyzed using *t*-tests for independent samples. Duration of the phases, stability variables, vertical linear velocity of the barbell, and vertical height of barbell were analyzed by a two-way (level × phase) analysis of variance (ANOVA, repeated measures). The angular kinematics were compared by a two-way (level × joint) ANOVA. When significant main effects or interactions were found, Post-hoc tests were performed to determine the effects by means of a Bonferroni test. Effect size (η^2) and statistical power analysis values were used to interpret the magnitude of the main and interaction effects. Significance level was set at $p \leq 0.05$. The results of the statistical analysis were acquired by means of IBM SPSS statistics software, version 20.0 (SPSS Inc., Chicago, IL, USA).

2.2 Failed Snatch Based on the Human & Bar Combination Barycenter

2.2.1 Subjects

The data were collected during the 2016 men's Chinese Olympic Trials. The top six place getters in the men's 69 kg category of snatch competition were selected, and the technical performances of their maximum weights for successful and unsuccessful in the snatch were selected for analysis. The selection criteria for the unsuccessful performances are that the moment of failure must occur in the support completion phase, and all the unsuccessful performances are forward falling to facilitate the data analysis. The Chinese Olympic Trials is the first-tier (the highest level) weightlifting event in China, These six lifters were members of the Chinese National Weightlifting Team. Between them, they had won three Olympic Games gold medals, two World Championships gold medals, and one Asian Games gold medal.

They are the top-elite lifters in China. Data on age, body mass, height, and their best result are shown in Table 2. This study was authorized by the Ethics Committee of Zhejiang College of Sports. Before taking part in the study, all subjects were informed of the objectives, experimental procedures and risks associated with this study. All subjects gave consent to participate in this study.

Table 2 The characteristics of subjects (n=6).

Subjects	Age (y)	Body mass (kg)	Height (m)	heaviest successful weight (kg)	heaviest unsuccessful weight (kg)
1	29	29	1.71	158	161
2	23	23	1.69	157	160
3	27	27	1.68	157	157
4	26	26	1.70	156	158
5	27	27	1.68	155	152
6	26	26	1.71	152	154

2.2.2 Experimental design

2.2.2.1 Kinematics analysis

Camera system: In order to determine the kinematic parameters of the barbell and human body, video and a computerized technique were employed. Two cameras (SONY HDR-FX1000 at 50 Hz) were set up in the horizontal plane, approximately 10 meters away from the subjects. The optical axis of each camera formed an angle of 45 degrees with the frontal plane of the subject (Figure 4-a). The position and focal length of the cameras remained unchanged during the whole process of snatch lift. The raw position-time data were smoothed by a low-pass digital filter with a cut-off frequency of 4 Hz[40], [159].

Coordinate system: Before the start of the competition, a PEAK 3D framework was used to calibrate the movement space (Figure 4-b). The spatial coordinates of various points were calculated from the collected video by means of direct linear transformation (DLT) method. The coordinate system is set as follows: the positive *X*-axis direction is directly behind the lifter, the positive *Y*-axis direction is on the right side of the lifter,

and the positive *Z*-axis direction is vertically upward (Figure 4-c).

2.2.2.2 Data collection and calculation

Phases division: previous researchers have divided the snatch process into six phases, including the first pull, the transition, the second pull, the turnover under the barbell, the catch phase, and the rising from squat position, based on the changes in the direction of knee angle and the height of the barbell[26], [40], [160]–[162]. The first five phases were considered to be the most important phases of the snatch lift[159], [160], [163], [164]. In the present study, the snatch process (from start position to squat position) was divided into six phases (*M*1-*M*6, same as in the differences in key techniques of snatch between top-elite and sub-elite lifters) based on the changes in direction of the knee angle, the vertical velocity of barbell, and the vertical height of barbell (Figure 5).

Data collection: In order to acquire the kinematic parameters during the snatch lifts, seventeen key points on the barbell and the body were selected, which were manually digitized using the SIMI°Motion7.50 3D analysis system (Figure 6). These points included the head, left shoulder, right shoulder, left elbow, right elbow, left wrist, right wrist, left hip, right hip, left knee, right knee, left ankle bone, right ankle bone, left tiptoe, right tiptoe, left and right endpoints of barbell (same as in the differences in key techniques of snatch between top-elite and sub-elite lifters)[165]. *COG* position of body was calculated using Hanavan Body Mathematical Model in the SIMI°Motion7.50 3D analysis software. *COG* position of the barbell was obtained by calculating the geometric center from the coordinates of the two endpoints in the SIMI°Motion7.50 3D analysis software.

Our study selected several variables to evaluate the three principles of “Near”, “Fast” and “Low” and the characteristics of human & bar combination barycenter. In the present study, the minimum distance between the *COG* of body and *COG* of barbell during the barbell rising (L_{Hmin}) was selected as the parameter for assessing the “Near” principle. The maximum vertical rising velocity of the barbell (V_{max}) and the maximum

vertical height of barbell (H_{bmax}) were selected as parameters to assess the "Fast" principle[45]. At the end of *M3*, the lifter's body begin to squat down quickly, at which time the maximum falling acceleration of the *COG* of body (a_f); The distance between the *COG* of body and *COG* of barbell on the vertical axis at the end of *M4* (L_{Hz1}) and at the end of *M5* (L_{Hz2}); And the vertical height of *COG* of body (H_{bd5}) and of *COG* of barbell (H_{b5}) at the end of *M5* were selected as parameters for assessing the "Low" Principle. The experimental variables show in the abbreviations.

Human & bar combination barycenter calculation: the direct linear transformation (DLT) method was use to obtain the 3-D space coordinates of human movement. The original coordinate data of *COG* of barbell and *COG* of body were exported by the SIMI°Motion7.50 3D analysis system, and the position of Human & bar combination barycenter was calculated by the following formula.

Calculation of *X*-axis coordinates of Human & bar combination barycenter (X_c): the position of the *COG* of body on the *X*-axis is X_1, the position of the *COG* of barbell on the *X*-axis is X_2, the weight of lifter is M_1, the weight of barbell id M_2.

$$X_c=\frac{(X1\times M1+X2\times M2)}{(M1+M2)} \qquad (3\text{-}1)$$

Calculation of *Y*-axis coordinates of Human & bar combination barycenter (Y_c): the position of the *COG* of body on the *Y*-axis is Y_1, the position of the *COG* of barbell on the *Y*-axis is Y_2, the weight of lifter is M_1, the weight of barbell id M_2.

$$Y_c=\frac{(Y1\times M1+Y2\times M2)}{(M1+M2)} \qquad (3\text{-}2)$$

Calculation of *Z*-axis coordinates of Human & bar combination barycenter (Z_c): the position of the *COG* of body on the *Z*-axis is Z_1, the position of the *COG* of barbell on the *Z*-axis is Z_2, the weight of lifter is M_1, the weight of barbell id M_2.

$$Z_c=\frac{(Z1\times M1+Z2\times M2)}{(M1+M2)} \qquad (3\text{-}3)$$

2.2.3 Statistical analyses

The hypotheses of normal distribution and homogeneity of variance were analyzed via Kolmogorov- Smirnov and Levene's tests, respectively. Using Box-whisker plot to test outliers in variables. The data comparison was analyzed by Paired-sample T test, and calculated the linear variation with time of human & bar combination barycenter on *X*-axis using a linear regression equation. Significance level was set at $p \leq 0.05$. The results of the statistical analysis were acquired by means of IBM SPSS statistics software, version 20.0 (SPSS Inc., Chicago, IL, USA).

2.3 Ultrasonic Image Changes of Extracorporeal Shockwave Therapy for Patellar Tendinopathy

2.3.1 Patients

Between October 2016 and March 2017, 46 patients with 52 injured knees were initially assessed for eligibility and enrolled in this study. Patients were allocated randomly to a study group or a control group by an independent statistician who was blinded for characteristics of patients. During the treatments, 3 patients with 4 knees were lost to follow-up and excluded from the study. The study group consisted of 22 patients with 25 knees and the control group 21 patients with 23 knees. All patients in this study were active professional athletes. The patient demographic characteristics are shown in Table 3.

Table 3 Patient demographic characteristics (n=43).

	Study Group	Control Group
Number of patients / knees	22 / 25	21 / 23
Average age (y)	25.69±6.58	26.38±7.60
Gender, male / female	13 / 9	9 / 12
Height (cm)	185.18±14.32	187.69±16.64
Weight (Kg)	76.28±14.36	78.74±15.25
Years of participating in sports (y)	6.13±5.94	6.57±6.29
Sports participation		
Basketball	6	5
Football	5	4
Volleyball	3	5
Badminton	2	3
Martial art	3	2
Running	3	2

2.3.2 Inclusion and Exclusion Criteria

Chronic patellar tendinopathy is defined as recurrent pain and tenderness due to degenerative changes of patellar tendon for at least 6 months. The inclusion and exclusion patient selection criteria are shown below.

All patients were screened to meet the following inclusion criteria:

● Patients with diagnosis of chronic patellar tendinopathy confirmed by medical history or physical examination.

● Patients aged from 18 to 35 years old.

● Patients who understood the nature of the study participation and had ability to sign informed consent form.

● Patients with good general health.

All patients were screened to meet the following exclusion criteria:

● Patients with acute injury within 3 months.

● Patients with other knee diseases that require surgery.

● Patients with a history of knee surgery within 1 year.

● Patients who received other treatment within 4 weeks.

● Patients who were pregnant.

2.3.3 Experimental Design

The study design, procedures and informed consent procedure were approved by the Institutional Review Board of the Zhejiang Sports Hospital. All patients were required to sign an informed consent form before the study participation. This study is a randomized controlled trial with blinded participants and outcomes assessors, using two-group repeated measures design. The study group received 3 radial ESWT treatments without local anaesthesia at 1-week interval. The control group received rest intervention. The measurements were taken before intervention. Follow-up measurements were carried out at 3 and 6 months after the final ESWT treatment. The flow chart of the trial is shown in Figure 7.

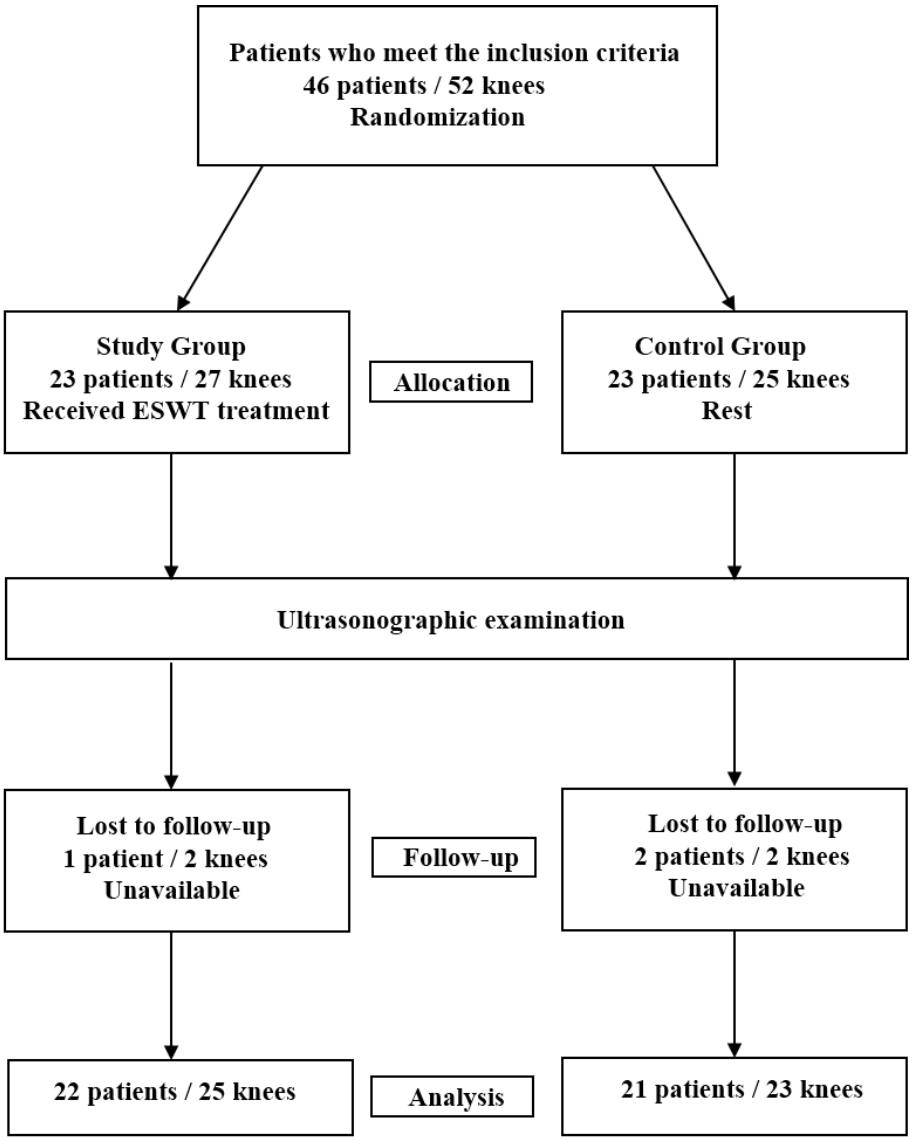

Figure 7 The flow diagram showing patients selection.

2.3.4 Intervention

ESWT intervention was carried out by 2 experienced independent physical therapists at Physical Rehabilitation Center of Zhejiang Sports Hospital. ESWT treatment was administered without local anaesthesia[143], [166], [167].

Study group:

Physical therapists explained the treatment procedure to patients and palpated the patellar tendon to find the most painful spot. ESWT was applied according to the operating instruction of the shockwave device (EMS Swiss Dolorclast Cart, Switzerland) and with the therapists' previous experience. Patients were in supine position with a slightly extended knee. All patients in the study group received 3 radial ESWT treatments without local anaesthesia at 1-week interval. Each session consists of 2000 impulses at 10 Hz. 500 impulses were performed around the point of maxima tenderness at a treatment intensity of 2 bar. Then the applicator was moved to the point of maxima tenderness, 500 impulses were given at intensity of 2, 2.5 and 3 bar respectively. 15 mm diameter applicator was selected. Transmission gel was applied between the applicator and the skin. Patients were allowed to resume light activities, however, heavy activities were not permitted for 6 months. In this study, all patients tolerated the procedure well without adverse complications.

Control group:

All patients in control group were treated with rest intervention only. They were also allowed to resume light activities, however, heavy activities were not permitted for 6 months.

2.3.5 Ultrasonographic Evaluation

The patellar tendon was imaged by an experienced musculoskeletal sonographer using a Philips ATL 5000 ultrasound machine with a 13MHz linear probe (Philips Medical Systems, Bothell, Washington). Before the intervention, 3 months and 6 months after the final treatment, ultrasound characteristics were collected by the same experienced sonographer who was blinded to the study protocol interpreted the results of ultrasonographic study.

The longitudinal length of the whole patellar tendon was measured on sagittal image (Figure 8). The thickness of proximal and distal (Figure 8) part of patellar tendon were measured on axial image. The proximal part was defined as the area where the patellar tendon attaches to the inferior pole of the patella, and the distal part as the area where it attaches to the tibial tuberosity. The data of hypo-echogenic and Calcifications (Figure 8) zones were also measured. All the measurements were performed on the images, which showed the largest values.

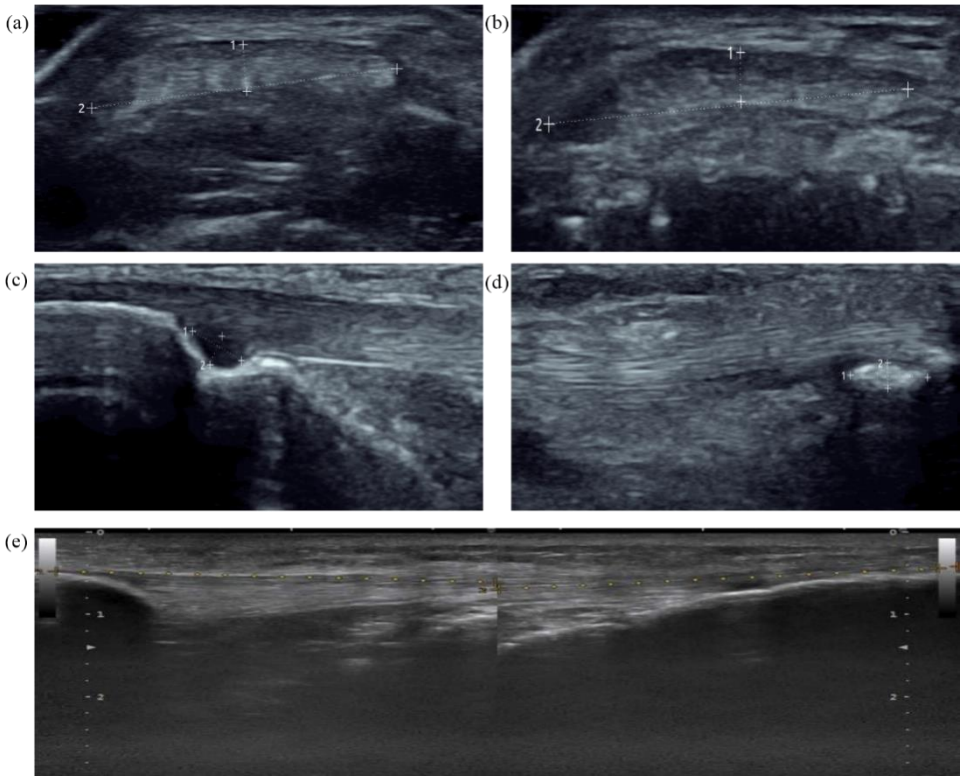

Figure 8 Ultrasound characteristics of patellar tendinopathy. (a) Thickness of proximal part of patellar tendon. (b) Thickness of distal part of patellar tendon. (c) Hypo-echogenic zones. (d) Calcifications zones. (e) Longitudinal length of patellar tendon.

2.3.6 Statistical Analyses

The data before and after intervention within the same group were compared statistically using a paired *t* test, the data between the study and control groups were compared with the *t*-tests for independent samples. Differences were considered statistically significant at $p<0.05$. The results of statistical analysis were acquired by means of IBM SPSS statistics software, version 20.0 (SPSS Inc., Chicago, IL, USA).

3 Results

3.1 Differences in key techniques of snatch between top-elite and sub-elite lifters

3.1.1 Kinematics analysis of barbell

The characteristics of top-elite and sub-elite lifters are presented in Table 1. As shown, the average age, height, and best result were significantly greater in top-elite lifters (t_{10}=5.115, p<0.05; t_{10}=3.151, p<0.05; t_{10}=5.211, p<0.05, respectively).

Table 4 Spatial-temporal characteristics of snatch lift (SD).

Variables (unit)	Phase	Top-Elite(n=6)	Sub-Elite(n=6)
TD (s)	*M1*	0.48(0.06)	0.53(0.09)
	M2	0.10(0.03)	0.13(0.04)
	M3	0.21(0.07)	0.17(0.06)
	M4	0.25(0.02)	0.26(0.03)
	M5	0.15(0.02)	0.15(0.02)
	M6	0.34(0.16)	0.31(0.07)
HB (cm)	*M1*	51.92(3.26)	45.93(5.78)
	M2	66.38(2.51)	55.80(7.61)*
	M3	89.90(2.89)	81.60(10.76)
	M4	117.97(2.81)	104.68(8.19)*
	M5	110.92(2.27)	102.22(9.85)
	M6	100.55(2.62)	93.15(5.18)*
HBR (%)	*M4*	69.61(2.06)	63.98(5.04)*
VB ($m \cdot s^{-1}$)	*M1*	1.05(0.11)	0.71(0.20)*
	M2	1.27(0.07)	1.00(0.18)*
	M3	1.74(0.10)	1.44(0.28)*
	M5	-0.73(0.11)	-0.56(0.18)
AB ($m \cdot s^{-2}$)	*M3*	4.59(0.85)	2.99(1.01)*

Note: * Statistically significant difference (p<0.05). - falling velocity.

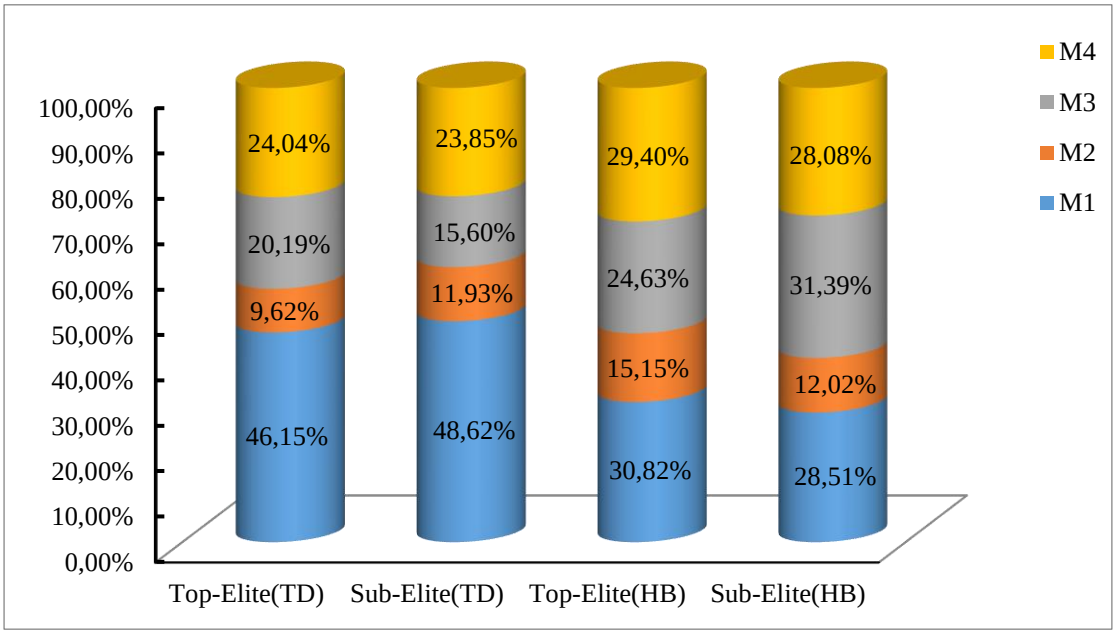

Figure 9 Proportion of *TD* and *HB* during *M1-M4* of top-elite and sub-elite lifters.

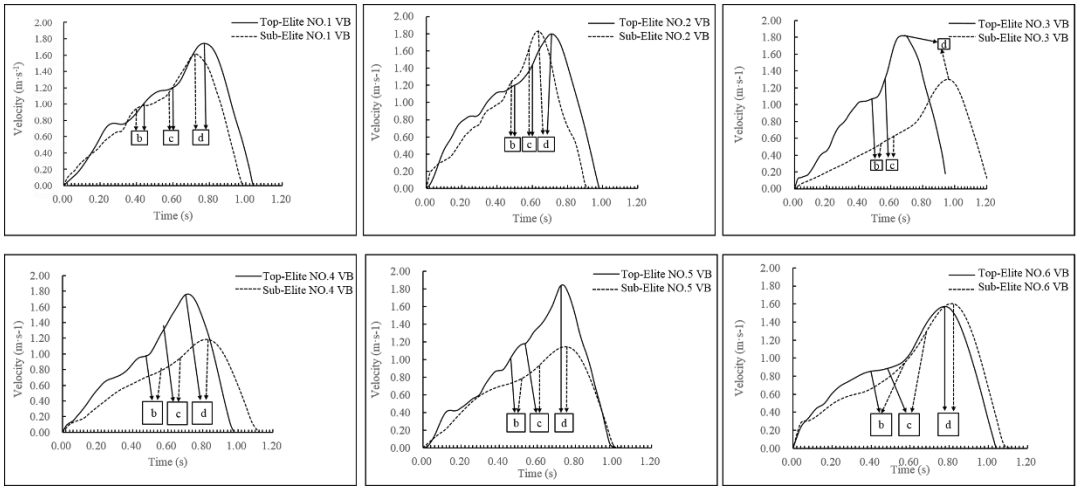

Figure 10 Variation of *VB* during *M1-M4* of the subjects included in the present study. Each figure depicted the comparison of one top-elite and one sub-elite lifter of the same rank in the list of Table 1. The points (b, c and d) correspond to the same instants in the snatch phases in Figure 5.

No significant interaction was observed between level and phase factors in *TD* ($F_{5,60}$=0.894, p>0.05, η^2=0.069, power=0.298) (Table 4). On the other hand, there was a significant main effect of the phase factor in *TD* ($F_{5,60}$=53.670, p<0.05, η^2=0.817, power=1.000). The results revealed that the duration of *M1* was the longest and *M2* was the shortest in all lifters.

There was no significant interaction between level and phase factors in *HB* ($F_{5,60}$=0.537, p>0.05, η^2=0.043, power=0.186). However, significant differences could be found between levels in *HB* at the end of *M2* ($F_{1,10}$=10.473, p<0.05, η^2=0.512, power=0.830), *M4* ($F_{1,10}$=14.119, p<0.05, η^2=0.585, power=0.922), and *M6* ($F_{1,10}$=9.744, p<0.05, η^2=0.494, power=9.744). The *HB* at the end of *M2*, *M4*, and *M6* were significantly greater in top-elite group. Furthermore, maximum *HBR* at the end of *M4* was significantly greater in top-elite lifters (t_{10}=2.600, p<0.05). It must be mentioned that significant differences were detected between phases in *HB* in top-elite ($F_{5,30}$=530.904, p<0.05, η^2=0.989, power=1.000) and in sub-elite ($F_{5,30}$=54.682, p<0.05, η^2=0.901, power=1.000). The *HB* at the end of *M4* was significantly greater than those of other phases in top-elite. Besides, the *HB* at the end of *M4* was significantly greater than those of the end of *M1*, *M2*, and *M3* in sub-elite.

No significant interaction was found between level and phase (*M1*-*M3*) factors in *VB* ($F_{2,30}$=0.166, p>0.05, η^2=0.011, power=0.073). On the other hand, significant differences between levels in *VB* at the end of *M1* ($F_{1,10}$=13.359, p<0.05, η^2=0.572, power=0.908), *M2* ($F_{1,10}$=11.067, p<0.05, η^2=0.525, power=0.850), and *M3* ($F_{1,10}$=6.140, p<0.05, η^2=0.380, power=0.609) could be detected. The *VB* at the end of *M1*, *M2*, and *M3* were significantly greater in top-elite lifters. Furthermore, maximum *AB* was significantly greater in top-elite lifters (t_{10}=2.983, p<0.05). In addition, significant differences were found between phases in *VB* in top-elite ($F_{2,15}$=82.831, p<0.05, η^2=0.917, power=1.000) and in sub-elite ($F_{2,15}$=16.099, p<0.05, η^2=0.682, power=0.997). The *VB* at the end of *M3* was significantly greater than those of the end of *M1* and *M2* in both levels. Moreover, the *VB* at the end of *M2* was significantly greater than that of *M1* in both levels.

3.1.2 Kinematics analysis of lower limb

Table 5 Kinematic characteristics of lower limb (SD).

Variables (unit)	Phase	Top-Elite(n=6)	Sub-Elite(n=6)
KA (degree)	Start position	64.92(13.28)	58.99(13.65)
	M1	127.20(9.12)	109.73(10.56)*
	M2	115.13(5.39)	101.45(10.23)*
	M3	154.79(8.91)	138.11(11.96)*
	M4	70.68(6.71)	70.87(6.12)
	M5	42.78(6.03)	47.94(7.02)
	M6	37.67(5.31)	40.36(5.85)
HA (degree)	Start position	45.84(8.10)	49.70(8.61)
	M1	89.63(11.94)	81.18(11.50)
	M2	117.92(7.39)	103.99(18.91)
	M3	147.05(8.20)	146.01(10.72)
	M4	105.47(8.57)	112.20(17.84)
	M5	54.35(10.35)	61.01(13.79)
	M6	48.32(7.81)	47.73(9.44)
KAV ($deg \cdot s^{-1}$)	*M1*	188.93(46.10)	173.31(50.23)
	M2	104.06(29.33)	58.79(35.54) *
	M3	307.31(124.69)	295.75(124.24)
	M4	471.50(102.96)	458.38(114.53)
	M5	343.09(75.77)	317.54(127.84)
	M6	40.96(36.83)	21.62(19.53)
HAV ($deg \cdot s^{-1}$)	*M1*	184.86(45.22)	144.92(37.10)
	M2	300.68(39.10)	224.47(107.97)
	M3	279.64(58.32)	352.11(91.27)
	M4	494.29(56.94)	376.37(82.54)*
	M5	504.36(55.20)	422.51(91.88)
	M6	18.10(15.55)	14.60(15.49)

Note: * Statistically significant difference ($p<0.05$).

No significant interaction was found between level and joint factors in the angle of the lower limb during all phases (Table 5). With regard to the knee angle, there were significant differences between levels in *KA* at the end of *M1* ($F_{1,10}$=9.417, $p<0.05$, η^2=0.485, power=0.790), *M2* ($F_{1,10}$=8.404, $p<0.05$, η^2=0.457, power=0.743), and *M3* ($F_{1,10}$=7.501, $p<0.05$, η^2=0.429, power=0.695). The extension *KA* at the end of *M1* and

M3 were significantly greater in top-elite lifters. In addition, the knee joint flexed approximately 12 degrees in top-elite lifters and 8 degrees in sub-elite lifters during *M2*, and the *KA* at the end of *M2* was significantly greater in top-elite lifters. Besides, significant differences were observed between joints in the lower limb angle in top-elite ($F_{1,10}$=37.525, p<0.05, η^2=0.790, power=1.000) and in sub-elite ($F_{1,10}$=20.068, p<0.05, η^2=0.667, power=0.980) at the end of *M1*. The extension *KA* was significantly greater than *HA* at the end of *M1* in both levels. Furthermore, there were significant differences between joints in the lower limb angle in top-elite ($F_{1,10}$=61.242, p<0.05, η^2=0.860, power=1.000) and in sub-elite ($F_{1,10}$=28.817, p<0.05, η^2=0.742, power=0.998) at the end of *M4*. The flexion *HA* was significantly greater than *KA* at the end of *M4* in both levels. Moreover, significant differences were found between joints in the lower limb angle in top-elite at the end of *M5* ($F_{1,10}$=5.598, p<0.05, η^2=0.359, power=0.570) and *M6* ($F_{1,10}$=7.628, p<0.05, η^2=0.433, power=0.702). The flexion *HA* were significantly greater than *KA* at the end of *M5* and *M6* in top-elite.

No significant interaction was detected between level and joint factors in the angular velocity of the lower limb in all phases. On the other hand, there were significant differences between levels in maximum flexion *KAV* during *M2* ($F_{1,10}$=5.792, p<0.05, η^2=0.367, power=0.584) and *HAV* during *M4* ($F_{1,10}$=8.298, p<0.05, η^2=0.453, power=0.738). The maximum flexion *KAV* in *M2* and *HAV* in *M4* were significantly greater in top-elite lifters. In addition, significant differences were detected between joints in maximum angular velocity in top-elite ($F_{1,10}$=97.093, p<0.05, η^2=0.907, power=1.000) and in sub-elite ($F_{1,10}$=12.748, p<0.05, η^2=0.560, power=0.895) during *M2*. The maximum extension *HAV* were significantly greater than flexion *KAV* during *M2* in both levels. Besides, there was a significant difference between joints in maximum angular velocity in top-elite ($F_{1,10}$=17.756, p<0.05, η^2=0.640, power=0.966) during *M5*. The maximum flexion *HAV* was significantly greater than *KAV* during *M5* in top-elite.

3.1.3 Analysis of stability of snatch technique

Table 6 Stability of snatch technique (SD).

Variables (unit)	Phase	Top-Elite(n=6)	Sub-elite(n=6)
BBCOG-X (cm)	Start position	8.20(1.12)	6.27(3.15)
	M1	7.50(1.44)	6.10(1.29)
	M2	4.13(0.62)	5.05(2.11)
	M3	12.83(2.57)	10.20(3.20)
	M4	10.90(1.12)	10.65(1.23)
	M5	1.48(0.99)	2.37(1.87)
	M6	4.93(2.83)	2.92(1.73)
BCOG-X (cm)	*M1*	4.40(2.51)	7.32(3.01)
	M2	6.33(2.29)	8.78(2.65)
	M3	6.88(2.09)	7.62(3.30)
	M4	8.95(3.22)	10.62(5.03)
	M5	12.57(3.30)	14.25(6.78)
	M6	17.08(6.32)	17.25(6.82)
BCOG-Y (cm)	*M1*	2.28(1.61)	2.48(1.78)
	M2	2.68(1.61)	2.95(2.62)
	M3	3.57(2.13)	3.71(3.33)
	M4	4.77(3.34)	4.68(2.85)
	M5	5.13(4.30)	6.22 (2.68)
	M6	5.90(4.81)	7.65(3.37)

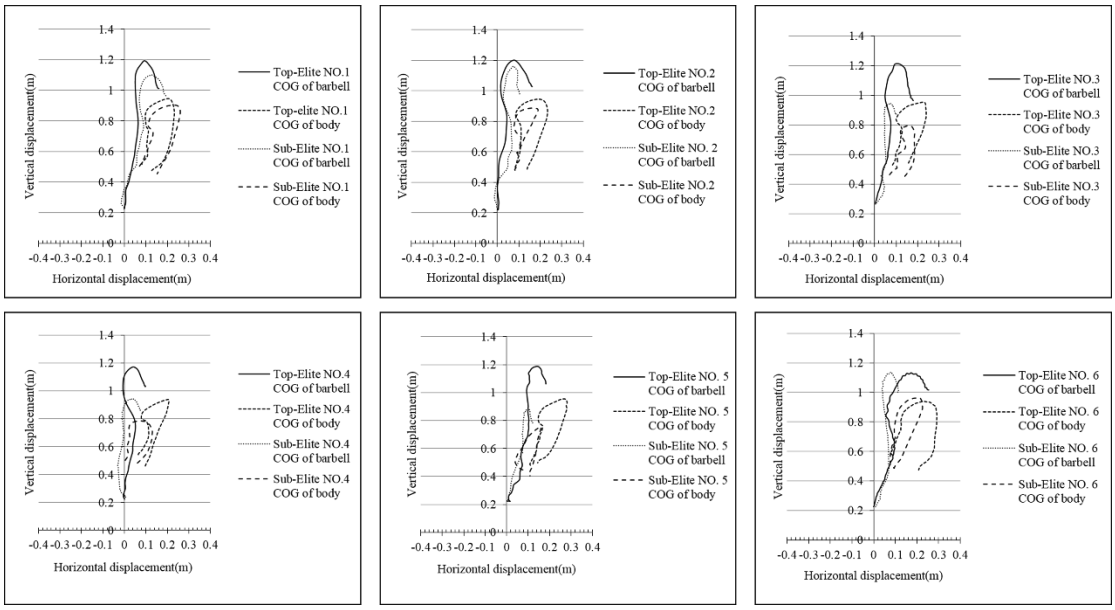

Figure 11 Trajectories of *COG* of barbell and body during snatch lifts of the subjects included in the present study. Each figure depicted the comparison of one top-elite and one sub-elite lifter of the same rank in the list of Table 1.

No significant interaction was observed between level and phase factors in maximum *BBCOG-X* ($F_{5,60}$=1.857, p>0.05, η^2=0.134, power=0.594), *BCOG-X* ($F_{5,60}$=0.171, p>0.05, η^2=0.014, power=0.087), and *BCOG-Y* ($F_{5,60}$=0.163, p>0.05, η^2=0.013, power=0.085) (Table 6). On the other hand, there were significant main effects of the phase factor in maximum *BBCOG-X* ($F_{5,60}$=49.240, p<0.05, η^2=0.808, power=1.000), *BCOG-X* ($F_{5,60}$=12.141, p<0.05, η^2=0.503, power=1.000), and *BCOG-Y* ($F_{5,60}$=3.788, p<0.05, η^2=0.240, power=0.915). The results revealed that the maximum *BBCOG-X* of top-elite in *M3* and sub-elite in *M4* were the largest, and in *M5* were the smallest in both levels. Besides, the maximum *BCOG-X* and *BCOG-Y* in *M6* were the longest and in *M1* were the shortest in both levels.

3.2 Failed Snatch Based on the Human & Bar Combination Barycenter

3.2.1 Comparison of the characteristics of "Near", "Fast" and "Low" principles

Comparison the successful and unsuccessful actions in snatch of the six lifters, the characteristics of "Near", "Fast" and "Low" principles are shown in Table 7. There were no significant differences between successful and unsuccessful actions in the minimum distance between the *COG* of body and *COG* of barbell during the barbell rising (L_{Hmin}), in the maximum vertical rising velocity of the barbell (V_{max}), in the maximum vertical height of barbell (H_{bmax}), in the vertical height of *COG* of body (H_{bd5}) and of *COG* of barbell (H_{b5}) at the end of *M5*, and in the distance between the *COG* of body and *COG* of barbell on the vertical axis at the end of *M5* (L_{Hz2}). Furthermore, there was no significant difference between successful and unsuccessful actions in the maximum falling acceleration of the *COG* of body (a_f) (t=0.159，P=0.88). In the successful action, the a_f is 0.1146m/s^2 greater than that in unsuccessful action. However, it is worth noting that the a_f of the top four lifters in successful and unsuccessful actions are greater than the acceleration of gravity g (9.8 m/s^2), and the a_f of the last two lifters are less than the acceleration of gravity g. In addition, significant difference (t=4.188, P=0.009) could be found between successful and unsuccessful actions in the distance between the *COG* of body and *COG* of barbell on the *Y*-axis at the end of *M4* (L_{Hz1}). The L_{Hz1} in successful action is 1.95cm larger than that in unsuccessful action.

Table 7 Comparative analysis of the action parameters of male snatch athletes.

	Successful	Unsuccessful	*P* value
L_{Hmin}（m）	0.0459±0.0093	0.0432±0.0116	0.649
V_{max}（m/s）	1.6233±0.1324	1.53±0.1587	0.199
H_{bmax}（m）	1.1708±0.0338	1.1703±0.0302	0.880
a_f（m/s^2）	-9.9583±2.8294	-9.8437±2.9122	0.335
L_{Hz1}（m）	0.5049±0.0362	0.4854±0.0325	0.009**
H_{b5}（m）	1.1005±0.0305	1.0945±0.0333	0.204
H_{bd5}（m）	0.5244±0.0215	0.5188±0.0315	0.437
L_{Hz2}（m）	0.5801±0.0489	0.5803±0.0186	0.983

Note: *p<0.05, **p<0.01, statistically significant difference

3.2.2 Comparison of the parameters in phases

In order to analyze the characteristics of snatch movement in more details, the snatch technique process is usually divided into several phases. In the present study, the complete snatch process is divided into six phases (Figure 5). Since the unsuccessful attempts all occur in the *M6* phase, the comparison of the parameters of phase characteristics of the successful and unsuccessful snatches does not include the *M6*. Comparative analysis the vertical displacement of the barbell of each phase, the duration of each phase, and the angles of the knee and hip joints at the end of each phase.

The comparison between the successful and unsuccessful motions in the vertical displacement and the duration of each phase, and the angles of the knee and hip joints at the end of each phase are shown in Table 8 and Table 9. In the present study, there was no significant difference between successful and unsuccessful snatches of the six lifters in the vertical displacement and duration of each phase, the angle of knee and hip joints at the end of each phase.

Table 8 Vertical displacement and duration of the barbell at each phase of the successful and unsuccessful snatch.

	Vertical displacement of each phase（m）		*P* value	Duration of each phase（s）		*P* value
	successful	unsuccessful		successful	unsuccessful	
M1	0.516±0.0592	0.5132±0.0397	0.849	0.46±0.0620	0.47±0.0576	0.695
M2	0.1237±0.0471	0.1183±0.0587	0.705	0.11±0.0486	0.1167±0.0463	0.732
M3	0.2645±0.0652	0.2745±0.0484	0.665	0.2033±0.0794	0.1917±0.0546	0.745
M4	0.2832±0.0168	0.2818±0.0177	0.871	0.2567±0.0197	0.2567±0.0082	1.00
M5	-0.0703±0.0056	-0.0758±0.0092	0.268	0.1533±0.0242	0.1567±0.0233	0.611

Table 9 Knee and hip joint angles at each phase of successful and unsuccessful snatch.

	KA（degree）		*P* value	*HA*（degree）		*P* value
	successful	unsuccessful		successful	unsuccessful	
M1	123.92±13.71	127.91±8.95	0.523	86.31±5.42	92.12±15.33	0.458
M2	111.38±7.95	118.54±9.39	0.258	113.59±8.57	112.59±7.49	0.792
M3	150.85±8.45	153.58±6.26	0.306	149.12±10.81	152.06±8.2	0.371
M4	71.35±7.26	71.44±9.53	0.985	111.19±12.99	103.71±22.96	0.259
M5	43.73±7.43	47.19±13.18	0.283	55.15±11.69	61.62±20.35	0.16

3.2.3 Comparison of human & bar combination barycenter

The "combination barycenter" is derived from the calculation of the *COG* of combined objects in physics. The human and bar combination barycenter is to view the lifter and barbell as a whole, the combination barycenter of the *COG* of body and barbell. The concept of human and bar combination barycenter was proposed by researcher Wang Yunde in 1984[46], however, it has not been studied in depth. Before calculating the human and bar combination barycenter, the data are first unified, and the 3-D coordinates of the successful and unsuccessful attempts of all lifters are defined as X (the positive *X*-axis direction is directly behind the lifter), Y (the positive *Y*-axis direction is on the right side of the lifter), and Z (the positive *Z*-axis direction is vertically upward). Set the 3-D coordinates of the *COG* of barbell before the snatch to (0, 0, 0.225), and the corresponding 3-D coordinates of the *COG* of body are processed accordingly, so that the 3-D coordinates at the beginning of all snatches are consistent. The comparison of the human and bar combination barycenter between the successful and unsuccessful snatches in the X, Y and Z axis are shown in Figure 12, Figure 13 and Figure 14.

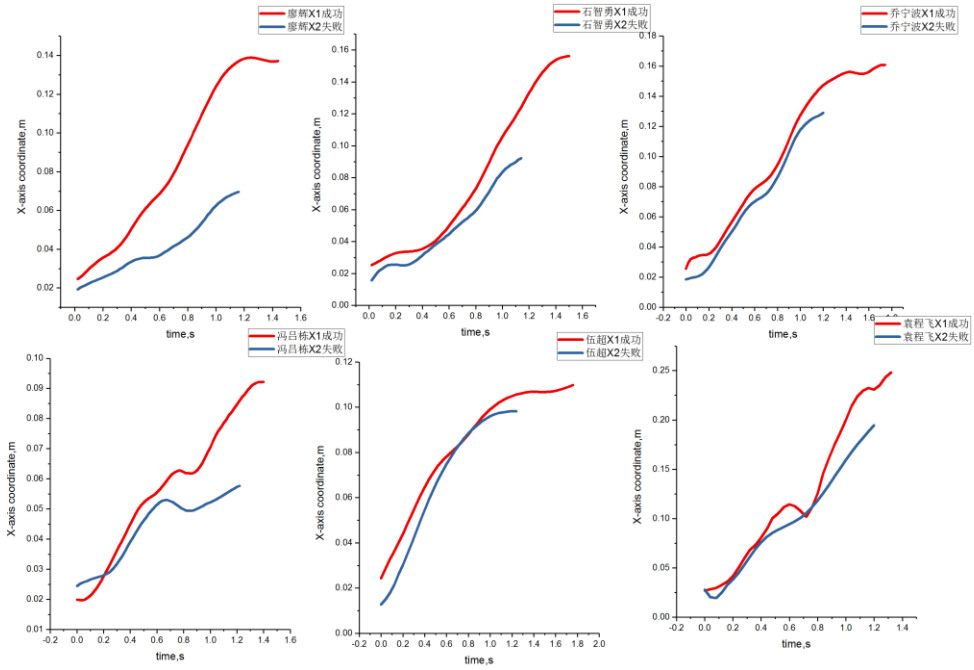

Figure 12 The trajectory of the human & bar combination barycenter of successful and unsuccessful snatch in the *X*-axis.

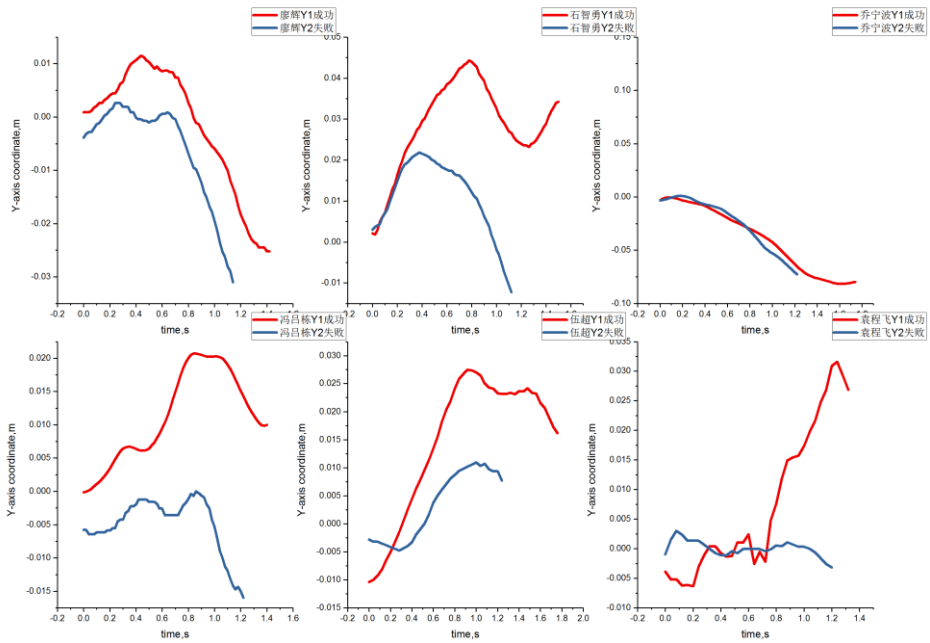

Figure 13 The trajectory of the human & bar combination barycenter of successful and unsuccessful snatch in the *Y*-axis.

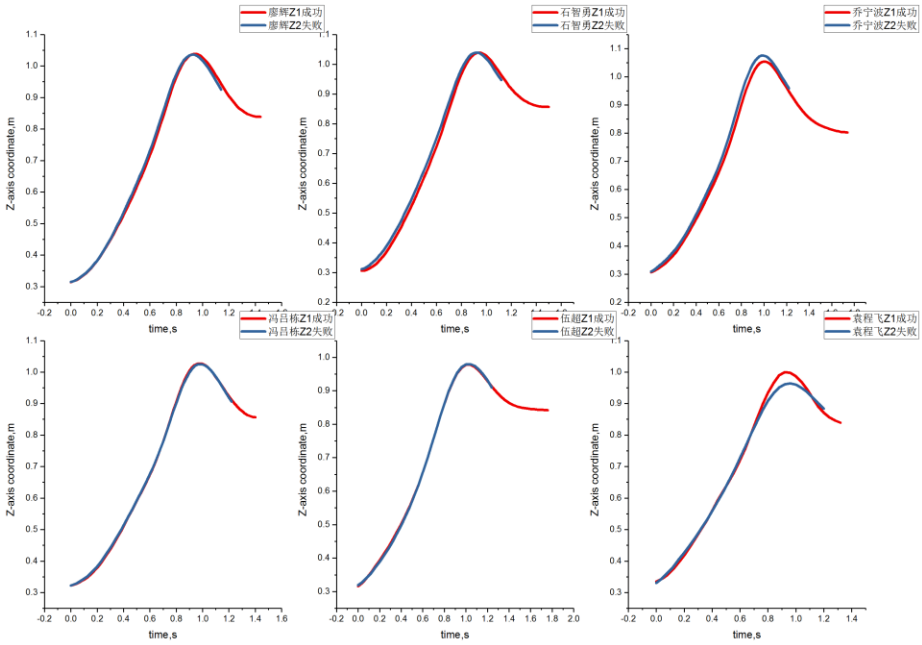

Figure 14 The trajectory of the human & bar combination barycenter of successful and unsuccessful snatch in the *Z*-axis.

The trajectory changes of the human & bar combination barycenter of the successful and unsuccessful snatches on the *X*-axis are shown in Figure 12. The displacement on the *X*-axis of human & bar combination barycenter in six lifters all increase with time, and the slopes of successful snatch of all lifters are higher than that of unsuccessful snatch. Figure 13 shows the trajectory changes of human & bar combination barycenter of successful and unsuccessful snatches on the *Y*-axis. The offsets of all lifters on the *Y*-axis are very small, and there is no obvious change rule. Figure 14 shows the trajectory changes of the human & bar combination barycenter on the *Z*-axis. The trajectories of human & bar combination barycenter of successful and unsuccessful on the *Z*-axis show a trend of rising first and then decreasing, and trajectories of successful and unsuccessful show a high degree of consistency.

In order to further verify the effect of the human & bar combination barycenter on the technical characteristics of excellent weightlifters, the present study intercepted the characteristic values of the human & bar combination barycenter on the *X*-axis at the characteristic pictures of each phase in snatch lift and calculated the change value of

each phase, and compared the difference of success and failure on the *X*-axis of the human & bar combination barycenter. Secondly, this study used the method of calculating the cumulative variation to analyze the difference of the human & bar combination barycenter on the *Y*-axis and *Z*-axis between the successful and unsuccessful actions.

Table 10 The displacement of the human & bar combination center at the moment the snatch succeed and unsuccessful on the *X*-axis (cm).

	Value of characteristic pictures		*P* value		Variation of phases		*P* value
	successful	unsuccessful			successful	unsuccessful	
a	0.0244±0.0024	0.0197±0.0056	0.126				
b	0.0612±0.0149	0.0538±0.0172	0.048	*M1*	0.0368±0.0137	0.0341±0.0163	0.484
c	0.0729±0.0218	0.0611±0.0198	0.077	*M2*	0.0117±0.01	0.0073±0.0037	0.263
d	0.0842±0.0149	0.0732±0.0269	0.199	*M3*	0.0113±0.0108	0.0121±0.0089	0.907
e	0.1245±0.0431	0.0986±0.0419	0.027	*M4*	0.0403±0.0316	0.0254±0.0191	0.048
f	0.1377±0.0478	0.107±0.0496	0.014	*M5*	0.0132±0.0063	0.0085±0.0094	0.048

The table 10 shows the comparison of displacement of the human & bar combination barycenter at the characteristic pictures of each phase in snatch lift and displacement change of each phase of successful and unsuccessful on the *X*-axis. There are significant differences in the displacement parameters on the *X*-axis of the human & bar combination barycenter between successful and unsuccessful at the end of *M1*, *M4* and *M5* (t=2.599, P<0.05; t=3.092, P<0.05; t=3.686, P<0.05). There was no statistical difference at the beginning of *M1*, the end of *M2* and *M3* (t=1.832, P=0.126; t=2.223, P=0.077; t=1.478, P=0.199). Since the change of the human & bar combination barycenter on the *X*-axis shows an upward trend, the change value of barbell of phases were used to represent the change of each phase. Figure 12 shows that there were significant difference in the variation of human & bar combination barycenter between successful and unsuccessful on the *X*-axis in the phase of *M4* and *M5* (t= 2.597, P<0.05; t= 2.606, P<0.05). In the other three phases (*M1*, *M2*, and *M3*), there was no significant difference between success and failure of the changes of human & bar combination barycenter on the *X*-axis (t=0.756, P=0.448; t=1.262, P=0.263; t=-0.123, P=0.907).

Table 11 The comparison for cumulative change of the human & bar combination barycenter of successful and unsuccessful snatch on the *Y*-axis and *Z*-axis.

	Y-axis		*P* value	*Z*-axis		*P* value
	successful	unsuccessful		successful	unsuccessful	
M1	1.6152±0.939	1.2684±0.8596	0.284	25.4609±5.2002	26.0027±3.0178	0.731
M2	0.3033±0.1258	0.2213±0.16	0.186	9.1615±4.6041	10.4759±4.6125	0.477
M3	0.9506±0.5275	0.5368±0.3997	0.154	23.0592±6.3086	21.4418±4.3348	0.597
M4	1.1632±0.7481	1.1413±0.7136	0.954	14.1116±1.9669	13.2899±2.2817	0.499
M5	0.7647±0.3775	0.7769±0.3915	0.949	8.3824±1.6755	8.2613±1.3577	0.855

Since the change of human & bar combination barycenter fluctuates on the *Y*-axis and *Z*-axis, the cumulative variation in phases is used to analyze the characteristics of the success and failure of the snatch (Figure 14). Assuming that there n frames in each phase, the calculation formula of the cumulative variation (Y_{cn}) of the human & bar combination barycenter in this phase is as follows (the calculation of Z_{cn} and Y_{cn} is the same):

$$Y_{cn}=|Yc2-Yc1|+|Yc3-Yc2|\cdots+|Ycn-Yc(n-1)| \qquad (3\text{-}4)$$

The results showed that there is no significant difference in the cumulative variation of the human & bar combination barycenter on the *Y*-axis at each phase between success and failure (t=1.2, P=0.284; t=1.53, P=0.186; t=1.68, P=0.154; t=0.06, P=0.954; t=-0.067, P=0.949). And there is no significant difference in the cumulative variation of the human & bar combination barycenter on the *Z*-axis at each phase between success and failure (t=-0.364, P=0.731; t=-0.768, P=0.477; t=0.564, P=0.597; t=0.728, P=0.499; t=0.192, P=0.855).

3.2.4 Analysis of the regression equation of the human & bar combination barycenter on the *X*-axis during the phase of *M5*

Taking time as the independent variable (χ), and the value of human & bar combination barycenter on the *X*-axis as dependent variable (y). The regression equation model was used to establish a linear unitary regression equation model for the success and failure of weightlifters in the phase of *M5* (Table 12, Table 13). The fitting degree of each linear regression equation model is represented by the R^2 value, and the R^2 value of all

regression equation models is greater than 0.85, which indicating that the data is well fitted and linear. The *t*-test of all independent variables of the regression equation is less than 0.001, and the sample regression coefficient (the slope of the regression line) of each athlete between success and failure of all linear regression equation models, the success is greater than failure.

Table 12 R^2 value of linear regression equation model of *X*-axis variation trend for the human & bar combination barycenter.

subjects	successful		unsuccessful	
	R^2	*P* value	R^2	*P* value
1	0.982	0.000	0.983	0.000
2	0.997	0.000	0.982	0.000
3	0.979	0.000	0.926	0.000
4	0.966	0.000	0.968	0.000
5	0.962	0.000	0.881	0.000
6	0.981	0.000	0.998	0.000

Table 13 Linear regression equation model of *X*-axis variation trend of the human & bar combination barycenter.

subjects	successful	unsuccessful
1	y=-0.007+0.129χ	y=-0.008 +0.07 χ
2	y=-0.043+0.151χ	y=-0.019+0.103χ
3	y=-0.008+0.132χ	y=-0.013+0.1χ
4	y=0.006+0.065χ	y=0.031+0.021χ
5	y=0.058+0.04χ	y=0.073+0.022χ
6	y=-0.125+0.319χ	y=-0.036+0.194χ

3.3 Ultrasonic Image Changes of Extracorporeal Shockwave Therapy for Patellar Tendinopathy

The results of the longitudinal length of patellar tendon, proximal and distal thickness of patellar tendon, hypo-echogenic zones, and calcifications zones are summarized in Table 14.

Table 14 Comparison of image changes between ESWT group and control group.

	Study Group (22 patients / 25 knees)	Control Group (21 patients / 23 knees)
Longitudinal length of patellar tendon (cm)		
Before intervention	5.69±0.46	5.49±0.64
3 months after final intervention	5.52±0.47*	5.43±0.62
6 months after final intervention	5.49±0.40*	5.40±0.59
Proximal thickness of patellar tendon (cm)		
Before intervention	0.50±0.03	0.50±0.06
3 months after final intervention	0.47±0.03*	0.49±0.05
6 months after final intervention	0.45±0.02**	0.48±0.06
Distal thickness of patellar tendon (cm)		
Before intervention	0.54±0.03	0.52±0.05
3 months after final intervention	0.46±0.03**△	0.50±0.04
6 months after final intervention	0.46±0.02**△	0.50±0.05
Hypo-echogenic zones (cm^2)		
Before intervention	0.746±0.325	0.672±0.328
3 months after final intervention	0.532±0.242**	0.663±0.315
6 months after final intervention	0.287±0.212**△	0.567±0.264*
Calcifications zones (cm^2)		
Before intervention	0.255±0.168	0.264±0.154
3 months after final intervention	0.187±0.121*	0.261±0.132
6 months after final intervention	0.159±0.131*△	0.253±0.104

Note. *p<0.05, **p<0.01, statistically significant difference between before and after intervention of the same group. △p<0.05, statistically significant difference between the ESWT group and the control group.

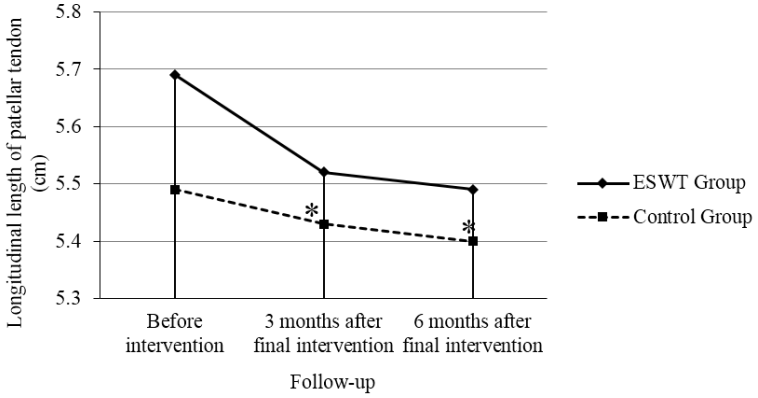

Figure 15 Comparison of changes between ESWT and control groups in longitudinal length of patellar tendon. *p<0.05, statistically significant difference between before and after intervention of the same group.

The longitudinal length of patellar tendon before intervention, 3 and 6 months after the final ESWT intervention in study and control groups were 5.69±0.46 cm versus (VS) 5.49±0.64 cm, 5.52±0.47 cm VS 5.43±0.62 cm, and 5.49±0.40 cm VS 5.40±0.59 cm, respectively (Figure 15). No significant difference was detected between the ESWT and control groups at before intervention, 3 and 6 months after the final ESWT intervention. Significant differences could be observed between 3 months after the final ESWT treatment and before intervention (p<0.05), and between 6 months after the final ESWT treatment and before intervention (p<0.05) in study group. The longitudinal length of patellar tendon at 3 and 6 months after the final ESWT treatment were significantly shorter than that of before intervention in EWST group. No significant difference was found between the three measurements in control group.

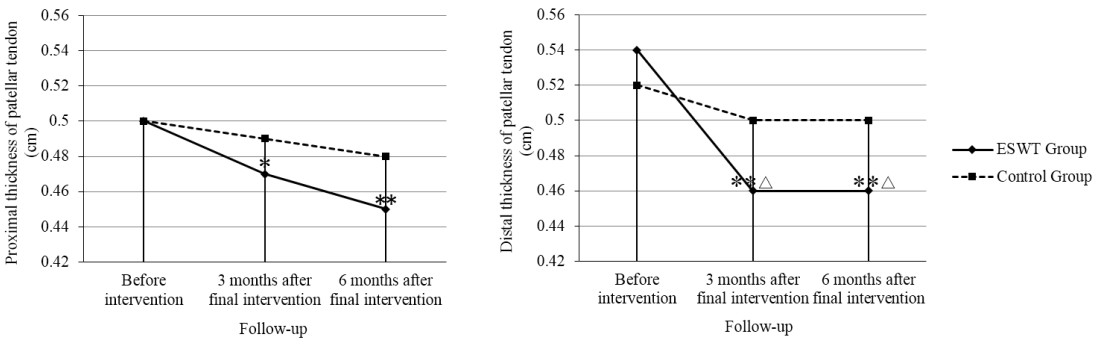

Figure 16 Comparison of changes between ESWT and control groups in thickness of patellar tendon. *p<0.05, **p<0.01, statistically significant difference between before and after intervention of the same group. △p<0.05, statistically significant difference between the ESWT group and the control group.

The proximal thickness of patellar tendon at before intervention, 3 and 6 months after the final ESWT intervention in study and control groups were 0.50±0.03 cm VS 0.50±0.06 cm, 0.47±0.03 cm VS 0.49±0.05 cm, and 0.45±0.02 cm VS 0.48±0.06 cm, respectively (Figure 16). No significant difference was observed between the ESWT and control groups at before intervention, 3 and 6 months after the final ESWT intervention. Significant differences were found between 3 months after the final ESWT treatment and before intervention (p<0.05), and between 6 months after the final ESWT treatment and before intervention (p<0.01) in study group. The proximal thickness of patellar tendon at 3 and 6 months after the final ESWT treatment were significantly thinner than that of before intervention in EWST group. There was no significant difference between the three measurements in control group.

The distal thickness of patellar tendon at before intervention, 3 and 6 months after the final ESWT intervention in study and control groups were 0.54±0.03 cm VS 0.52±0.05 cm, 0.46±0.03 cm VS 0.50±0.04 cm, and 0.46±0.02 cm VS 0.50±0.05 cm, respectively. No significant difference was found between the ESWT and control groups at before intervention. However, the distal thickness of patellar tendon of ESWT group were significantly thinner than that of control group at 3 and 6 months after the final ESWT treatment (p<0.05). Furthermore, Significant differences were observed between 3 months after the final ESWT treatment and before intervention (p<0.01), and between 6 months after the final ESWT treatment and before intervention (p<0.01) in

study group. The distal thickness of patellar tendon at 3 and 6 months after the final ESWT treatment were significantly thinner than that of before intervention in EWST group. No significant difference was detected between the three measurements in control group.

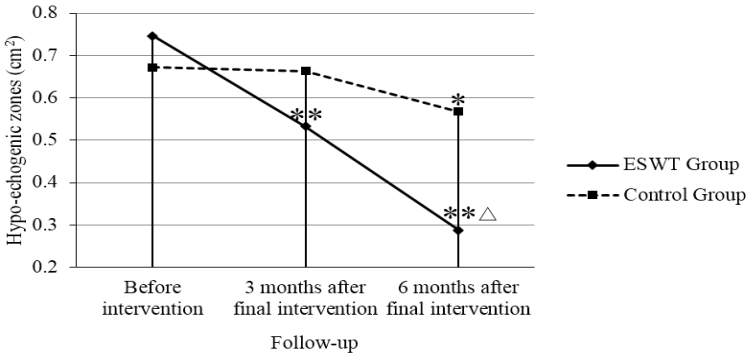

Figure 17 Comparison of changes between ESWT and control groups in hypo-echogenic zones. *p<0.05, **p<0.01, statistically significant difference between before and after intervention of the same group. $^{\triangle}p$<0.05, statistically significant difference between the ESWT group and the control group.

The hypo-echogenic zones at before intervention, 3 and 6 months after the final ESWT intervention in study and control groups were 0.746±0.325 cm^2 VS 0.672±0.328 cm^2, 0.532±0.242 cm^2 VS 0.663±0.315 cm^2, and 0.287±0.212 cm^2 VS 0.567±0.264 cm^2, respectively. There was no significant difference between the ESWT and control groups at before intervention and 3 months after the final ESWT treatment (Figure 17). However, the hypo-echogenic zones of ESWT group were significantly smaller than that of control group at 6 months after the final ESWT treatment (p<0.05). Furthermore, Significant differences were found between 3 months after the final ESWT treatment and before intervention (p<0.01), and between 6 months after the final ESWT treatment and before intervention (p<0.01) in study group. The hypo-echogenic zones at 3 and 6 months after the final ESWT treatment were significantly smaller than that of before intervention in EWST group. Moreover, the hypo-echogenic zones at 6 months after the final ESWT treatment was significantly smaller than that of before intervention in control group (p<0.05).

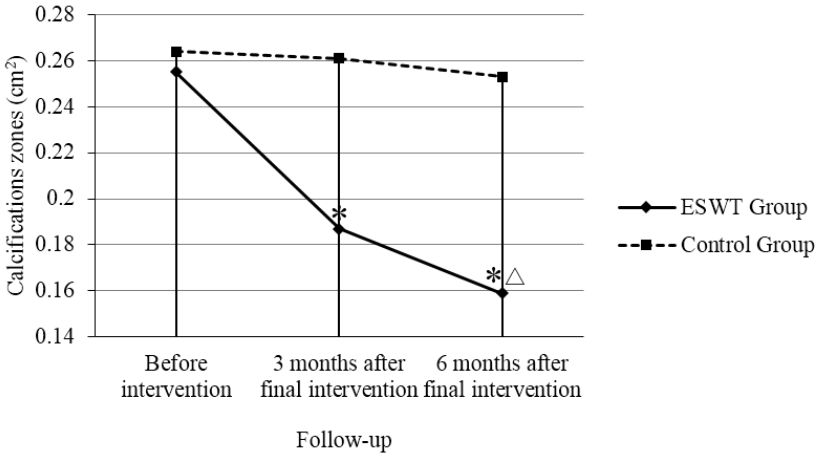

Figure 18 Comparison of changes between ESWT and control groups in calcifications zones. *p<0.05, statistically significant difference between before and after intervention of the same group. △p<0.05, statistically significant difference between the ESWT group and the control group.

The calcifications zones at before intervention, 3 and 6 months after the final ESWT intervention in study and control groups were 0.255±0.168 cm^2 VS 0.264±0.154 cm^2, 0.187±0.121 cm^2 VS 0.261±0.132 cm^2, and 0.159±0.131 cm^2 VS 0.253±0.104 cm^2, respectively. There was no significant difference between the ESWT and control groups at before intervention and 3 months after the final ESWT treatment (Figure 18). However, the calcifications zones of ESWT group were significantly smaller than that of control group at 6 months after the final ESWT treatment (p<0.05). Furthermore, Significant differences were found between 3 months after the final ESWT treatment and before intervention (p<0.05), and between 6 months after the final ESWT treatment and before intervention (p<0.05) in study group. No significant difference was observed between the three measurements in control group.

Finally, due to this applied therapy, more than 90% (23 of 25 in the study group VS 17 of 21 in the control group) of the athletes who participated in my study not only could return to their professional sport carrier, but also many of them achieved excellent results.

4 Discussion

4.1 Differences in key techniques of snatch between top-elite and sub-elite lifters

Male weightlifting is a sport with a long history dating back to being included in the first Olympic Games in 1896. This sport is based on dynamic strength and power, in which two different movements (Snatch and Clean & Jerk) are performed sequentially. The final rank is determined on the total result of the heaviest successful lifts of the two movements. In weightlifting, athletes use their reasonable technique, physical, functional and psychological traits to lift a barbell of maximal weight. Of all weight classes in Olympic weightlifting, only the 69-kg is the category common to both genders. The 69-kg class, which is identified as the category with the greatest depth of lifters from top to bottom is representative of national caliber performance in snatch[168]. The performance pattern of snatch technique requires the barbell to be lifted from the floor to a straight-arm overhead position in a continuous action[26], [159], [160], [163], [164]. In the past four Olympic Games (2004, 2008, 2012, and 2016) Chinese male athletes have won the gold medals in the 69-kg class which provides an adequate ground for our investigation.

The technique of top-elite athletes represents the best performance, and can be considered as excellent technical model or a reference that should be achieved. Previous studies of snatch performance focused mainly on the differences in adult female weightlifters[168]–[170], between adult and adolescent males[163], and between genders[28], [40], [159]. They analyzed the kinematic and kinetic parameters by two or three-dimensional methods. However, the lack of data regarding the stability of snatch technique raises questions regarding the appropriateness of using the specific assistant exercises for improving the success of the snatch lift. Furthermore, no study was found within the literature that compared the snatch performances between top-elite and sub-elite (lower level athletes) male weightlifters in 69-kg category.

Therefore, the purpose of our study was to highlight the differences of technical characteristics between top-elite and sub-elite male weightlifters, to summarize the

technical features of top-elite athletes, and to provide valuable information for lower level lifters and coaches to integrate into training and competition. The results revealed that the technical patterns of the two levels have differences in the analyzed parameters.

4.1.1 Spatial-temporal characteristics of barbell

It was reported in a previous study that higher skilled lifters employed an optimum sequential pattern of intersegmental coordination and executed longer barbell positive acceleration phases compared with less skilled[171], [172]. Figure 9 showed the percentage of duration of phases and vertical displacement of the barbell during *M1*-*M4*. The analysis of the time sequence of phases revealed that the two levels used different time structures. Sub-elite lifters used a longer initial phase (*M1*) and transition phase (*M2*). On the contrary, top-elite lifters used a longer decisive phase (*M3*). Therefore, it seemed that sub-elite lifters tended to increase the concentric muscle activity in *M1* and the eccentric muscle activity in *M2*. However, top-elite lifters tended to increase the decisive phase.

In general terms, a longer propulsive trajectory allows lifters to act upon the barbell longer, and this results in a better condition to apply force on the barbell. Previous studies reported that shorter lifters moved the barbell less than taller lifters, which was disadvantageous for driving the barbell[173]. However, the maximum vertical height of the barbell for a successful lift for shorter lifters does not need to be as high as taller lifters. From this perspective, athletes with lower height can translate this into an advantage. In the present study, the maximum vertical height and maximum relative vertical height (normalized by athletes' height) of the barbell at the end of *M4* were significantly greater in top-elite lifters. It was reported that the maximum vertical height of the barbell in the snatch lift of male elite lifters was 1.25m, although this value was 1.15m in another study[159], [163]. In our study, the maximum vertical height of the barbell was 1.18m (*HBR*: 69.61%) in top-elite lifters and 1.05m (*HBR*: 63.98%) in sub-elite lifters. The main reason for the inconsistency for the maximum vertical height of the barbell might be due to the physical differences of the subjects.

The movement of the barbell is as a result of the force that a lifter can exert on it. The displacement-time, velocity-time relationships, and acceleration of the barbell are often seen as important criterions for both coaches and athletes to evaluate weightlifting technique[26], [29]. There were two types of velocity curves for the snatch lift of elite weightlifters that are worthy to discuss and analyze in details. The first one, with a continuous increase of the barbell's vertical velocity from *M1* to *M3*, was characterized by better weightlifters, and the second was that the barbell's vertical velocity had a slight decrease in *M2*[26]. In the present study, the barbell's vertical velocity increased continuously from *M1* to *M3* both in top-elite and sub-elite lifters (Figure 10), which were consistent with the better velocity curve patterns of previous study.

It was reported that the increase of the mass of the barbell could result in a decrease in vertical velocity and maximum height of the barbell[168]. In our study, although the barbell mass was significantly greater in top-elite, the maximal vertical linear velocity, the maximal vertical height, the maximal vertical acceleration, and maximum relative vertical height (normalized by athletes' height) of barbell were significantly greater in top-elite athletes. Firstly, these were inconsistent with previous findings since the data in literature obtained from same group of subjects, however, the data in our study were regained from different groups of subjects. Moreover, these inconsistencies might be attributed to the higher ability of the top-elite lifters included in our study.

4.1.2 Angular kinematics

Earlier studies reported that the knee joint in *M2* and the hip joint in *M3* have great importance during the snatch lift[29], [160], and the extensor muscles around knee and hip joints can conduce to the control of antagonistic muscles in a sequence motion of the snatch lift, especially the first three phases[29]. In the present study, top-elite showed significantly greater extension values than sub-elite at the knee joint at the end of *M1* and *M3* and significantly greater flexion values than sub-elite at the knee joint at the end of *M2*.

During the lift, a common pattern of leg action was observed. In both levels, the knee

angle reached the first maximum extension value at the end of *M1* and then decreased slightly in *M2*. At the end of *M3*, the second maximum extension angle of knee occurred. The second phase (*M2*) is highly critical and should be performed quickly with a small knee flexion to be effective in the snatch lift[29], [160], [164], [174]. The flexion of the knee joint during *M2* should be executed rapidly enough to store recoverable elastic energy and to elicit stretch reflex facilitation immediately following the concentric contraction of knee joint extensor muscles[175]. In the present study, the sub-elite lifters showed less flexion (8 degrees vs. 12 degrees) and significantly slower angular velocity of the knee joint than top-elite lifters during *M2*.

It was reported that the maximum extension velocity of the hip joint was greater than the maximum extension velocity of the knee joint during *M3*, which could increase the acceleration of the barbell and contribute to the execution of an explosive second pull[164]. In the present study, the maximum angular velocity of the hip joint was significantly greater than that of the knee joint during *M3* in sub-elite, which in line with previous studies. However, the finding was opposite in top-elite. This difference between the two levels may be due to the barbell weight of top-elite group being significantly greater than that of sub-elite group.

4.1.3 Stability of snatch technique

Regarding the characteristics of stability in the snatch technique, the horizontal (anterior-posterior) movement proved to be an important factor in performing a successful snatch technique. The extent of the horizontal movement of the barbell indicated the instability involved or the correction required to complete the lift, and the horizontal displacement caused an additional acceleration and work during lift[26], [176]. Therefore, the anterior-posterior displacement of the barbell during the pull phase was considered an effective application of muscle power, and a small horizontal movement is essential for good lifting technique and unnecessary energy consumption[29], [164]. In our study, maximum *BBCOG-X*, *BCOG-X*, and *BCOG-Y* (Table 6) were used to evaluate the stability of the snatch lift. A previous study reported

that the barbell displaced horizontally by 10-20 cm during the snatch lifts in elite lifters[177]. These *BCOG-X* values were close to those in the present study (top-elite: 17.08 cm and sub-elite: 17.25 cm, respectively). In addition, no significant difference was found between top-elite and sub-elite lifters in the three parameters. This result revealed that sub-elite lifters used their energy as effectively as top-elite.

With respect to barbell trajectory, several researches investigated the optimal lifting motion patterns for snatch weightlifting[26], [178], [179]. However, there was no unified point of view between researchers because of the different optimization criterion such as actuating torque and power consumption cost. In a previous study, the barbell trajectory of elite athletes moved to the rear of the body, not through the vertical reference line that projected upward from the initial position of the barbell[26]. In the present study, the trajectories of all the six top-elite lifters did not pass the vertical reference line (Figure 11) which were in line with the findings of this study.

4.2 Failed Snatch Based on the Human & Bar Combination Barycenter

The technical principle of the snatch shows that weightlifters need to follow the three principles of "Near", "Fast" and "Low" during the snatch process[33], [34]. "Near" means that the barbell is required to be as close to the body as possible during the lifting, which is determined by the horizontal distance (L_H) between the *COG* of barbell and the *COG* of the body (two centers). M is the weight of the barbell, L_H is the distance from the *COG* of barbell to the *COG* of the human body, and W is the resistance moment of the barbell to the *COG* of body. Based on $W_{(t)}=M \cdot L_{H(t)}$, when M is unchanged, the smaller L_H is, the smaller W is, which means that the weightlifters have less effort[30]. "Fast" means that pulling the barbell and action force should be fast, which is determined by the maximum velocity of the end of the force phase (V_{max}), which is $V_{max0}=\sqrt{2gh}$, in which h is the optimal height for lifters to squat. When h is too large, energy is wasted, and if h is too small, the squat to support barbell cannot be completed. At this moment, the maximum velocity (V_{max}) is the most appropriate initial velocity (V_{max0})[30]. "Low" refers to requiring lifters to reduce the *COG* of body at the fastest

speed to facilitate the support to the barbell, which is determined by the biggest falling acceleration (a_f) of *COG* of body during the squat support stage. Previous research reported that the a_f of elite lifters is greater than the acceleration of gravity g[30].

Previous study reported that the failed snatch of most elite lifters occurred during the support completion phase[20]. Therefore, it is speculated that the main reason for failure of forward or backward is that the relative position of the *COG* of barbell and body on the sagittal plan exceeds the lifters' control limit. Since the trajectory of the *COG* of barbell will be different of every attempt of each lifter, and there is a certain relationship between the trajectories of the *COG* of barbell and *COG* of body, Therefore, it is difficult to find the difference between successful and unsuccessful attempts only from the trajectory of the barbell's center of gravity and the trajectory of the human's center of gravity. In this case, the human & bar combination barycenter may be a good choice. The present study proposes to use the human & bar combination barycenter as one of the parameters. The concept of human & bar combination barycenter was first coined by Wang in 1984[46]. However, due to the technical limitations, the characteristics and the roles of human & bar combination barycenter were not explained in the research at that time.

The present study selected the technical performance of the top 6 place getters of the 2016 men's Chinese Olympic Trials as the research subjects, and analyzed the three principles of "Near", "Fast", and "Low", the phased principle, and the human & bar combination barycenter. The purpose of this study is to exposit the differences between successful and unsuccessful characteristics of snatch attempts in competition, and to explore the biomechanical factors that cause the failed snatch.

4.2.1 Analysis of the "Near", "Fast" and "Low" principles and the parameters in phases

The snatch can be divided into two parts: the first part is from the moment of barbell starts to rise to the barbell's maximum vertical speed; the second part is from the beginning of the barbell's inertial rise to the athlete's squatting and receiving the barbell. The first part can be divided into three phases: knee extension phase (*M1*), knee flexion phase (*M2*), and force phase (*M3*). This part is mainly for athletes to lift the barbell, give the barbell an upward force, so that the barbell can gain a certain speed and height and obtain the most appropriate initial speed (V_{max0}) at the end of the force phase. The second part can be divided into three stages: the inertial ascent stage (*M4*), the squat support stage (*M5*), and the support completion stage (*M6*). The second part mainly uses the speed obtained in the first part to make the barbell continue to inertially rise, while relying on "swing arms and turning wrists"[180] which make the barbell continue to gain a certain speed during the ascent. At the same time, the reaction force of the barbell acts on the human body to make the athlete's center of gravity obtain greater downward acceleration, so as to quickly squat to complete the supporting and receiving barbell. And as the weight of the barbell increases, the speed of "swing arms and turning wrists" also increases [181], [182].

Previous studies[25], [183]–[186]pointed out that insufficient knee flexion in the knee flexion phase is one of the important factors leading to the failure of the snatch. At the knee flexion phase, athletes need to fully draw the knee and actively extend the hip. On the contrary, that is, the knee is not fully flexed, and the extension of the hip joint is limited. The present study compared the characteristics of the successful and failed attempts of six athletes. In the first part, the minimum distance between the *COG* of the barbell and the *COG* of the body (two centers), the maximum speed of the barbell during the ascent process, the time indexes, the space indexes, and the joints angle are all compared. There is no statistical difference, which showed that there was no obvious difference in the indicators between the success and failure in the first part of the snatch movement, which is consistent with related research[35], [44]. Although there is no statistical difference between all the indicators, some indicators are still worthy of our

attention. The probability of negating the null hypothesis is more than 70%, and it has very important significance for technical actions[187]. Among them, the average value of the knee angle at the end of the knee flexion phase of the successful attempts is 7.16° smaller than that of failed attempts, and there is a 74.2% probability that negate the success and failure are equal. The maximum speed obtained by the barbell at the end of the force stage of a successful lift is 0.0933m/s greater than that of the failure, and there is an 80.1% probability that negate success and failure are equal. Insufficient knee flexion will affect the secondary force and will inevitably affect the maximum speed of the barbell. It may be a potential factor for snatch failure. However, in this study, due to research limitations, it cannot be confirmed that the direct cause of snatch failure is insufficient knee flexion.

The research of Wang et al. [20] showed that the maximum vertical distance between the *COG* of body and *COG* of barbell (two centers) is not enough to form a good support posture, which may be the main reason for the failure of the snatch. The researches of Gourgoulis [35], [44] et al. pointed out that there is no significant difference in the temporal and spatial characteristics between successful and failed snatch attempts. In this study, the successful and failed attempts of 6 athletes were compared. In addition to the significant difference in the vertical distance between the *COG* of body and *COG* of barbell at the end of the inertial ascent stage (*M4*) in the second part, there are no significant differences in the vertical acceleration of body, time indexes, spatial indicators and joint angles. There is no significant difference in the maximum height of barbell at the end of the inertial ascent stage (*M4*) between the successful and failed attempts, the average difference is only 0.05cm. And the vertical distance between the *COG* of body and *COG* of barbell (two centers) is different at the end of the inertial ascent stage (*M4*), the L_{Hz1} of successful snatch is 1.95cm larger than that of failed snatch, which indicates that the lowering speed of the *COG* of body of successful attempt is higher than that of failed attempt in the inertial ascent stage (*M4*). At the same time, the average knee and hip angles of the successful attempt at the end of the squat support stage (*M5*) are less than those of the failed attempt. However, there is no significant difference in the height of barbell, the height of *COG* of body, and the

vertical distance between the *COG* of body and *COG* of barbell (two centers) at the end of the squat support stage (*M5*). Based on these, the insufficient support space may be one of the reasons for failure which pointed out in related study [20], and the conclusion lacks sufficient evidence. The results of the present study are basically consistent with the results of Gourgoulis [35], [44]et al.

4.2.2 Analysis of the human & bar combination barycenter

The human & bar combination barycenter is the center of gravity formed by the combination of the *COG* of body and *COG* of barbell. The change of the human & bar combination barycenter is affected by the change of the *COG* of body and *COG* of barbell. The change of the human & bar combination barycenter on the *Y*-axis indicates that the left and right deviation of the *COG* of body and *COG* of barbell during the snatch. The smaller the cumulative change of the *Y*-axis in each phase, the smaller offset of the *COG* of body and *COG* of barbell (two centers) at this stage, and more stable snatch technique. The results of the present study show that the human & bar combination barycenter on the *Y*-axis of successful attempts is greater than the failure but there is no significant difference (Figure 13). There is no significant difference in the cumulative change of the human & bar combination barycenter on the *Z*-axis, and Figure 14 shows that the *Z*-axis change of the human & bar combination barycenter for successful and failed snatches tends to be consistent.

Comparing the changes of the human & bar combination barycenter on the *X*-axis between the successful and failed attempts, it is found that the values of the end of knee extension phase (*M1*), the end of the inertial ascent stage (*M4*), and the end of the squat support stage (*M5*) are statistically different. And the changes in the inertial ascent stage (*M4*) and in the squat support stage (*M5*) are also statistically different. And all the successful attempts are greater than the failed attempts. The average value of human & bar combination barycenter on the *X*-axis at the end of knee extension phase (*M1*) of successful attempts is 0.0732cm larger than the failed attempts. The average value of human & bar combination barycenter on the *X*-axis at the end of the inertial ascent stage

(*M4*) of successful attempts is 2.59cm larger than the failed attempts. The average value of human & bar combination barycenter on the *X*-axis at the end of the squat support stage (*M5*) of successful attempts is 3.07cm larger than the failed attempts. The variation of human & bar combination barycenter on the *X*-axis in the inertial ascent stage (*M4*) of successful attempts is 1.49cm larger than the failed attempts. And the variation of human & bar combination barycenter on the *X*-axis in the squat support stage (*M5*) of successful attempts is 0.471cm larger than the failed attempts. These indicate that the key problems of success and failure are caused by the insufficient increase of human & bar combination barycenter on the *X*-axis during the inertial ascent stage (*M4*) and the squat support stage (*M5*).

At the same time, this study established the unitary regression equation from the beginning of the inertial ascent stage (*M4*) to the end of the squat support stage (*M5*) of the success and failure of 6 athletes through the unitary regression equation model. It can be seen from Table 13 that the slope of the regression line for success is greater than that for failure. Figure 19 shows the changes of *COG* of barbell, *COG* of body, and human & bar combination barycenter on the *X*-axis during the entire snatch process. It is not difficult to see that the gap of the human & bar combination barycenter between successful and failed attempts is getting bigger and bigger over time, especially, after the mark point (the beginning of the inertial ascent stage), the slope of the human & bar combination barycenter of successful is obviously higher than that of the failure. The trajectory of the *COG* of barbell shows a trend of falling first and then rising at this stage, while the trajectory of *COG* of body shows the opposite trend of rising first and then failing. If weightlifters want to maintain the continuous growth of the human & bar combination barycenter, they need to reduce the downward trend of the *COG* of barbell and increase the growth trend of the *COG* of body.

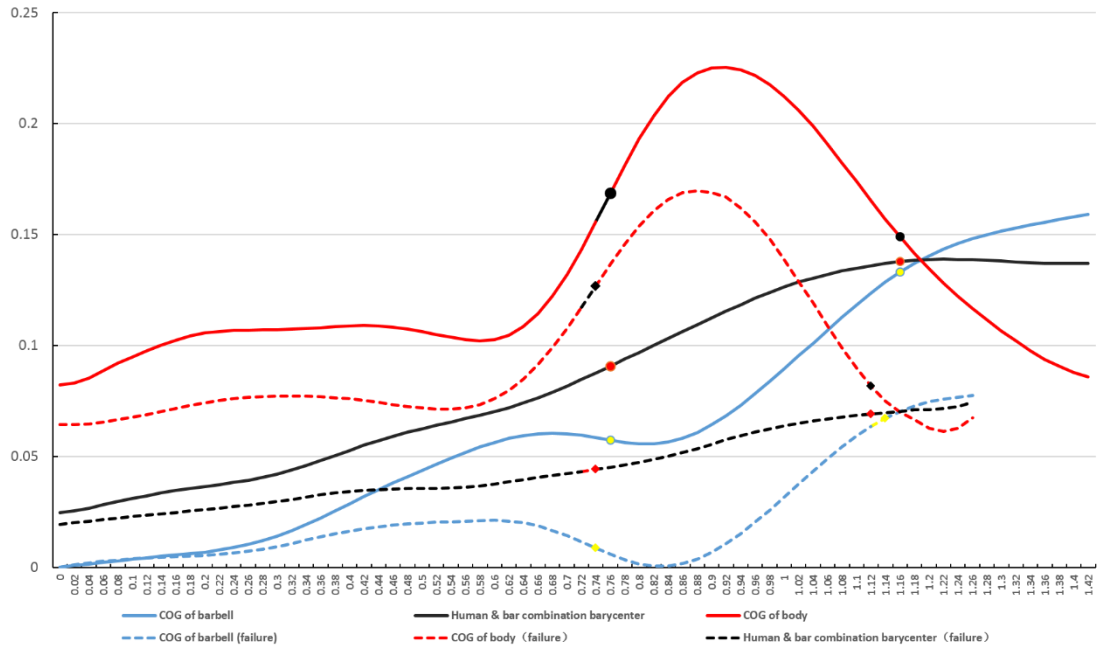

Figure 19 One athlete's successful and unsuccessful trajectories of the *COG* of barbell and body, human & bar combination barycenter on the *X*-axis.

From the perspective of technical action, the barbell obtains the maximum vertical speed after the force phase (*M3*) is over. At this time, the body's center of gravity drops rapidly, with the elbow joint as the center of the circle, and the forearm as the radius to swing the barbell to continue rising. Previous research [180] pointed out that since the barbell moves in an arc from the moment of the maximum speed to the moment of the maximum height, the force on the barbell during the process can be decomposed into a vertical upward force *F1* and a positive *X*-axis force *F2*. *F1* raises the barbell to the maximum height, *F2* brings the barbell close to the body and reaches the support position. If *F2* is too large, the barbell's center of gravity will move backward and cause the barbell to fall behind, and if *F2* is too small, it will cause the center of gravity of barbell to move forward and cause the barbell to fall forward. The power of *F1* mainly comes from the "swing arms and turning wrists" action, while the power of *F2* comes from the proper upper body reclining at the end the force phase (*M3*), and the muscles of the shoulders, waist and back give the barbell appropriate strength. At this stage, the body's center of gravity relies on the reaction force of the barbell and active hip and knee flexion to actively descend. It is worth noting that some studies have pointed out that the falling speed of the center of gravity of elite weightlifters should be greater than

the acceleration of gravity. In the present study, the maximum acceleration of the center of gravity of the first four weightlifters is greater than the acceleration of gravity, which shows that the technical movements of the latter two lifters still need to be strengthened.

The present study believes that the direct cause of the failure is that the human & bar combination barycenter has not reached the designated position, and the reason is insufficient recoil at the end of the force phase (*M3*). The research of Gourgoulis [35], [44]et al. showed that the difference in the vector direction of the resultant acceleration and the instability of the weightlifters' force direction during the knee extension phase (*M1*) are the main reasons for the failure of the snatch. The main reasons for the difference between the results of literatures and the present study may be: first, multiple levels of athletes (69kg, 77kg, 85kg) were selected in previous study, and individual athletes are quite different; second, they did not distinguish the type of failure (the barbell falls forward or backward); third, the secondary data (acceleration) is used as the main calculation value, and the possibility of error is greater.

In summary, after compared and analyzed the movement characteristics of weightlifters' successful and failed snatch (forward fall), it is concluded that the direct cause of the athlete's failure is that the position of the human & bar combination barycenter on the *X*-axis is more forward than the position of the successful attempts at the end of the squat support stage (*M5*). The reasons are that the upper body does not lean back properly at the end of the force phase (*M3*), and the shoulder, waist, and back muscles are not used to give proper force to barbell, which leads to the growth rate of the human & bar combination barycenter on the *X*-axis is insufficient during the inertial ascent stage (*M4*) and the squat support stage (*M5*), and resulting in failure to reach the proper position of the barbell center of gravity at the squat support stage (*M5*), and finally causing the snatch failure. Of course, insufficient knee flexion in the knee flexion phase (*M2*) leads to insufficient secondary force, which causes the maximum vertical speed of barbell to be too low, and it may also be an indirect factor that causes the snatch failure. Insufficient maximum vertical speed may cause the lifters to use more power for barbell rising during the inertial ascent stage (*M4*), and reduce the force in the positive direction of the *X*-axis, which indirectly leads to the failure of the snatch.

And the difference of vertical distance between the *COG* of barbell and the *COG* of the body (two centers) at the end of the inertial ascent stage (*M4*) may be related to the above factors. Therefore, in the present study, the effectiveness of human & bar combination barycenter in judging the successful and failed attempts of outstanding weightlifters has been verified.

4.3 Ultrasonic Image Changes of Extracorporeal Shockwave Therapy for Patellar Tendinopathy

Patellar tendinopathy, also described as jumper's knee, is a common overuse injury of the patellar tendon causing pain at the inferior pole of the patella[188]. Prolonged repetitive stress of the knee-extensor apparatus, as in jumping, landing, running, and cutting activities, can lead to this tendinopathy in different sports[189]. The overall prevalence of patellar tendinopathy is high in elite and non-elite athletes[59], [190], [191]. Prevalence is particularly higher in sports characterized by high demands on speed and power for leg extensors, such as volleyball (44.6%) and basketball (31.9%)[59]. Because of its chronicity, patellar tendinopathy has substantial impact on the career of many athletes and for some, it is the reason to end their career prematurely[55], [190], [192]–[194].

There is no consensus on what is the most beneficial treatment strategy for patellar tendinopathy based on the current literatures[54], [195]. Conservative treatments (e.g. physical therapy, anti-inflammatory medication, rest, exercise) have been recommended as the initial treatments of option for chronic patellar tendinopathy, but the results of many conservative treatments were irregular and inconsistent, and the symptoms frequently recurred[194], [196],[197]. When conservative treatment failed, patients always proceed to surgical treatment[54], [195]. However, the results of surgery are unpredictable, and surgery is inevitably related to surgical risk and complications[198], [199].

Extracorporeal shockwave therapy (ESWT) can play a role in the management of tendon pain and should be incorporated into a more comprehensive training

rehabilitation plan. ESWT was used for some chronic tendinopathies from 1990. As a non-invasive and safe therapy, it was originally used to pulverize kidney stones[200]. ESWT is now being used for the treatment of musculoskeletal conditions such as chronic proximal plantar fasciitis[201] and lateral epicondylitis[202]. Nowadays, ESWT has gained popularity in physiotherapists and clinicians with varying reports of positive effects for patellar tendinopathy.

Numerous studies performed randomized trials to evaluate the effectiveness of ESWT for patellar tendinopathy in patients who had not responded successfully to conservative treatments. They concluded that ESWT was positively contributed to the improvement of pain symptomatology and function in short- and long-term treatment of patellar tendinopathy[139], [203]–[206]. Peers *et al.* and Wang *et al.* reported that the effectiveness of ESWT for patellar tendinopathy in reducing pain and improving function was comparable with patellar tenotomy surgery and better than non-surgical treatments including nonsteroidal anti-inflammatory medication, physical therapy, exercise intervention[193],[119].

With the development of ultrasound technology, high-frequency ultrasound has a higher resolution for observing soft tissue and can measure subtle variations in diseased tissues. Recently, ultrasonographic evaluation is widely used for musculoskeletal disorders to assist diagnosis and guide therapy[207]. Ultrasonography is commonly accepted as a method to visualize patellar tendon structure based on its lower cost, availability, and direct clinical correlation. Furthermore, the ultrasonographic changes of patellar tendon tissues can be considered as essential evidence for assessing the effectiveness of ESWT for patellar tendinopathy that should be investigated.

The purpose of the current study was to observe the ultrasonic image changes of ESWT for patellar tendinopathy from the aspect of repairing the patellar tendon tissues, to study the mechanism of ESWT for patellar tendinopathy based on morphosis, and to discuss the value of musculoskeletal ultrasound in assessing the effectiveness of ESWT for patellar tendinopathy.

Musculoskeletal ultrasound has a high resolution and can present clear ultrasonic images for soft tissues. Therefore, musculoskeletal ultrasound was widely used of the diagnosis, adjuvant treatment, and evaluation for soft tissue diseases such as tendon, ligament, and muscle diseases [208]–[210]. Gellhorn *et al*. measured the length and cross-sectional area of patellar tendon using musculoskeletal ultrasound, and they concluded that the musculoskeletal ultrasound was reliable in measuring patellar tendon morphology parameters [211]. Patellar tendon morphology parameters not only provide valuable information for the diagnosis and treatment of patellar tendinopathy, but also can be used to assess the rehabilitation of patellar tendinopathy [146]. In the present study, musculoskeletal ultrasound was used to measure the changes of longitudinal length of patellar tendon, thickness of patellar tendon, hypo-echogenic zones, and calcifications zones before and after intervention in study and control groups. Discussing whether ESWT treatment for patellar tendinopathy can cause benign changes of patellar tendon.

The proximal part of the patellar tendon attaches to the inferior pole of the patella, and the distal part attaches to the tibial tuberosity. The main function of patellar tendon is to deliver the contraction force generated by quadriceps to the tibia, which in turn drives the calf movement. Therefore, patellar tendon is the focal and weak point of the power chain, and is a relatively vulnerable part. The patellar tendon is similar to elastic material. Under the action of external force, the patellar tendon can be elongated within a certain range. However, when the external force exceeds elastic limit, the elongation will cause patellar tendon degeneration, which lead to difficulty recovering to its original length. In this study, the longitudinal lengths of patellar tendon at 3 and 6 months after the final ESWT treatment significantly decreased compared with before intervention in EWST group (Figure 15). These indicated that ESWT treatment combined with rest could play a positive role in the patellar tendon retraction, and the effectiveness was better than rest only. The mechanism may be related to the fact that rest can relax the quadriceps and reduce the stress in the patellar tendon [72]. It may also be associated with that ESWT treatment can promote patellar tendon repair and elastic recovery.

Patellar tendon thickening can lead to decreased elasticity and biomechanical properties of the patellar tendon. In the current study, the proximal and distal patellar tendon thickness at 3 and 6 months after the final ESWT treatment were significantly thinner than that of before intervention in study group (Figure 16). These changes in study group showed that ESWT treatment combined with rest for patellar tendinopathy could decrease the patellar tendon thickness. This was consistent with the literature which reported that the patellar tendon thickening was reversible [119].

Hypoecho is a typical ultrasound manifestation, and it is also an important indicator of ultrasound diagnosis of patellar tendinopathy [212]. Observing changes of hypo-echogenic zones can indirectly study changes of patellar tendon structure caused by ESWT treatment. In current study, the hypo-echogenic zones at 3 months after final intervention significantly reduced compared with before intervention in study group (Figure 17). The hypo-echogenic zones at 6 months after final intervention were significantly reduced than before intervention in study and control groups. Moreover, the results of study group were better than control group (Figure 17). This indicated that both ESWT and rest can reduce the hypo-echogenic zones of patellar tendon, and the effect of ESWT combined with rest was better.

Excessive stress stimuli can cause subtle damage to the patellar tendon, which will lead to bone morphogenetic protein increasing in local bone and then result in patellar tendon calcification [53]. The calcification can result in hardening, reduced elasticity, and decreased mechanical properties to patellar tendon. Therefore, the improvement of patellar tendon calcification is an important goal of clinical treatment. In the present study, the calcifications zones at 3 and 6 months after final intervention significantly reduced compared with before intervention in ESWT group (Figure 18). Results of the current study showed that ESWT treatment combined with rest can reduce the calcified patellar tendinopathy. That is similar to previous study which reported that shockwave treatment on calcified supraspinatus tendonitis can reduce or eliminate local calcification area [213].

There are limitations in the current study. Only professional athletes were analyzed, which lead to relatively small number of patients included into this study. In addition, affected by training and competition factors, the length of follow-up was short. Furthermore, MRI has higher accuracy to observe changes in tissue structure, however, the costs are higher either. If it is possible, using musculoskeletal ultrasound in conjunction with MRI to study tissue changes may be a better option in future research.

5 Conclusions and future work

5.1 Conclusions

In the first part of our study described important aspects of snatch technique. Since the data were recorded under competition conditions, they could be used as reference not only for athletes and coaches to integrate into training and competition but also for future biomechanical research.

The findings of the present study demonstrated the similarities of the technical characteristics of snatch lift between the two levels. The major differences were observed in maximum *HB*, *HBR*, *VB*, and *AB*. Values of these parameters were significantly greater in top-elite lifters, which indicated that sub-elite lifters need to develop their skills in these parameters in order to reach the top-elite level. Coaches of sub-elite lifters should focus on exercises suitable to the strength characteristics of the *M1* and *M3*. In addition, sub-elite lifters showed significantly slower angular velocity of the knee joint compared with top-elite lifters in *M2*. Therefore, sub-elite lifters' flexor muscles of knee joint should be strengthened and their ability of generating and utilizing elastic energy in *M2* should be improved.

In the second part of our study compared the successful and failed snatch techniques of Chinese elite weightlifters, analyzed the characteristics of "Near", "Fast" and "Low" principles, and the parameters in phases and the parameters of human & bar combination barycenter. And established the regression equation of the human & bar combination barycenter on the *X*-axis during the inertial ascent stage (*M4*) and the squat

support stage (*M5*). And found the effectiveness of the human & bar combination barycenter in judging success and failure snatch. The main conclusions are as follows:(1) The direct cause of the failure of snatch is that the displacement of human & bar combination barycenter on the *X*-axis (front and back direction, sagittal axis) is not enough to reach the position for supporting barbell during the inertial ascent stage (*M4*) and the squat support stage (*M5*). The reason is that the strength of reclining at the end of the force phase (*M3*) is insufficient, so it is reminded that weightlifters who often fall forward in snatch should strengthen reclining exercises.(2) Insufficient flexion of the knee joint during the knee flexion phase (*M2*), which leads to a lower maximum vertical speed of barbell and difference of vertical distance between the *COG* of barbell and the *COG* of the body (two centers) at the end of the inertial ascent stage (*M4*), which may be an indirect factor leading to the failure of snatch. (3) The cumulative variation of human & bar combination barycenter on the *X*-axis (front and back direction, sagittal axis) can effectively determine the technical characteristics between the success and failure of elite weightlifters in snatch.

In the third part of our study demonstrated the ultrasonic image changes of extracorporeal shockwave therapy for patellar tendinopathy. Extracorporeal shockwave therapy combined with rest appeared to be more effective than rest intervention in repairing patellar tendon length, patellar tendon thickness, hypo-echogenic zones, and calcifications zones. Therefore, extracorporeal shockwave therapy for patellar tendinopathy can result in benign changes of patellar tendon. Due to this applied therapy, more than 90% of the athletes who participated in my study not only could return to their professional sport carrier, but also many of them achieved excellent results.

5.2 Recommendations for future works

1. To investigate the key technical characteristics of clean and jerk. In my thesis, the key features of snatch technique between top-elite and sub-elite weightlifters were compared. Results from this dissertation identified that the knee joint angle (*KA*) has the most significant effect on the snatch technique and the angular velocity of the knee

joint (*KAV*) during *M2* has also a particular effect on efficiency.

In weightlifting, two different movements (Snatch and Clean & Jerk) are performed sequentially. The final rank is determined on the total result of the heaviest successful lifts of the two movements. Therefore, snatch and clean & jerk have the same important status in weightlifting. The purpose of future work is to refine the technical characteristics of top-elite lifters, compare the differences in technical patterns between top-elite and sub-elite lifters, and provide valuable references for numerous lower level lifters to integrate into training and competition.

2. Continue to explore factors of other failed snatch based on the human & bar combination barycenter, such as the barbell falling behind. In my dissertation, the selection criteria for the unsuccessful performances are that the moment of failure must occur in the support completion phase, and all the unsuccessful performances are forward falling to facilitate the data analysis. Results from my study concluded that the key factor of failed snatch is the insufficient increase of human & bar combination barycenter on the *X*-axis during the *M*4 and *M*5 phases. If weightlifters can ensure the sufficient increase range of human & bar combination barycenter on the *X*-axis during *M*4-*M*5, then the success rate of snatch can be improved.

Forward falling of the barbell is one form of failed snatch, and behind falling of the barbell in the snatch is also a common form of failure. Therefore, future work analyzes the factors of behind falling, which has extraordinary significance for improving the success rate.

3. To investigate the treatment evaluation of the muscle strain of the biceps femoris and semitendinosus of professional athletes. In the present study, the morphological changes patella tendon of ESWT for patella tendinopathy have been observed by ultrasound imaging technology. The results from my thesis determined on professional, active athletes that Extracorporeal Shockwave Therapy (ESWT), combined with rest, can effectively improve the morphology of patella tendon, since the five main properties (proximal-, distal thickness, longitudinal length, hypo-echogenic, and calcifications zones) were significantly reduced.

Semitendinosus and biceps femoris strains are also common injuries in my

professional athletes, which seriously affect the training and competition. In my future work, we will cooperate with professional therapists to evaluate muscle reaction time, contraction height, contraction speed, recovery speed, etc., using EMG methods, and provide valuable support for professional athletes' injury rehabilitation training.

Thesis points

My thesis contains three parts, the topics are "**Differences in key techniques of snatch between top-elite and sub-elite lifters**", "**Failed snatch based on the human & bar combination barycenter**", and "**Ultrasonic image changes of extracorporeal shockwave therapy for patellar tendinopathy**" respectively. The thesis points as follow:

1st Thesis point: I experimentally identified that *M1-M3* phases will enhance the snatch technique and will make a significant difference between top-elite and sub-elite weightlifters. With regard to lower limb movement pattern, I recognized that the knee joint angle (*KA*) has the most significant effect on the snatch technique (see Figure 20). Because the barbell rising mainly relies on the knee extension in the first three phases, and the barbell height is the guarantee for snatch. Therefore, the strength of the lower limb is particularly important, and the ability to extend knee joint is the specific manifestation. Therefore, we can conclude that sub-elite lifters must develop their knee extension capability, similarly to top-elite lifters, to reach higher efficiency.

(2) I experimentally determined that the angular velocity of the knee joint (*KAV*) during *M2* has also a particular effect on efficiency (Figure 21). We can state that a higher angular velocity must be carried during *M2* in order to achieve the best performance if sub-elite and top-elite lifters are compared. Because the flexion of the knee joint during *M2* should rapidly enough to store recoverable elastic energy and to elicit stretch reflex immediately, which is beneficial to the force generation in M3. Just like the rapid squat before the jump in the vertical jump.

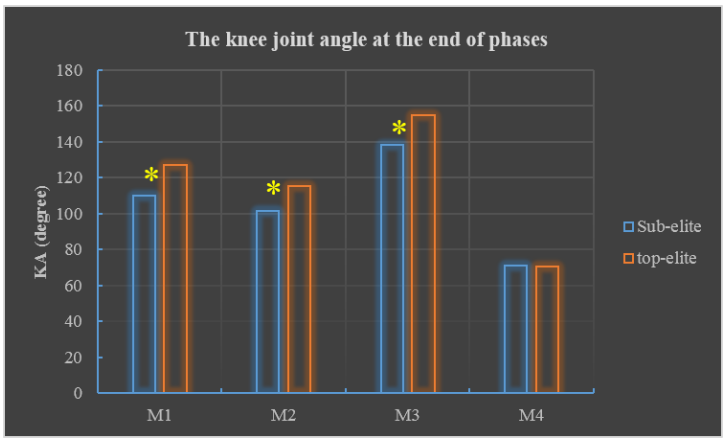

Figure 20 The knee joint angle at the end of phases between the top-elite and sub-elite weightlifters. *p<0.05, statistically significant difference

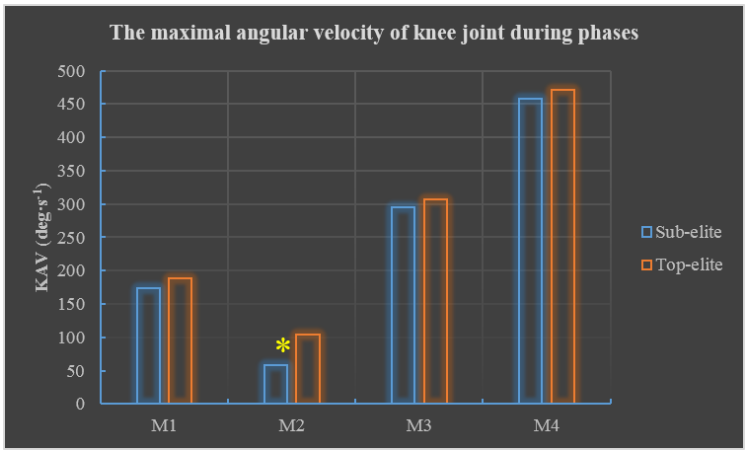

Figure 21 The maximal angular velocity of knee joint during *M*1-*M*4 phases between the top-elite and sub-elite weightlifters. *p<0.05, statistically significant difference.

Related articles of the 1st thesis point:

[1] **Liu Gongju**, Gusztáv Fekete, Hongchun Yang, Jing Ma, Dong Sun, Qichang Mei, Yaodong Gu, (2018). Comparative 3-dimensional kinematic analysis of snatch technique between top-elite and sub-elite male weightlifters in 69-kg category. *Heliyon*, 4(7), e00658. **Q1**

[2] **Liu Gongju**, Li Jianshe, Pan Huiju, (2019).Critical technique characteristics of snatch at nearly extreme mass of Olympic champions. *Journal of Beijing Sport University*, 42(9), 127-136.

[3] **Liu Gongju**, Bi Zhiyuan, Hu ting, (2015). Speed indicators analysis on the snatch in Chinese Male's small levels (56 to 77 kg class) weightlifting athletes. *Zhejiang Sport Science*, 37(5), 125-128.

2nd Thesis point: The three principle parameters ("Near", "Fast" and "Low") and its supplementary principle ("Phases") cannot effectively analyze the difference between successful and failed snatch technique. Based on the "combination barycenter" of combined objects in physics, for the first time in my thesis, the human & bar combination barycenter was used in practice and to judge the difference between the successful and failed snatch technique.

I concluded that the key factor of failed snatch is the insufficient increase of human & bar combination barycenter on the *X*-axis during the *M*4 and *M*5 phases. If weightlifters can ensure the sufficient increase range of human & bar combination barycenter on the *X*-axis during *M*4-*M*5, then the success rate of snatch can be improved. Because, the values of success is significantly greater than that of failure (Figure 22 and Figure 22), combined with the form of snatch action, we can concluded that the direct cause of failed snatch is the position of the human & bar combination barycenter on the *X*-axis is more forward at the end of *M5*.

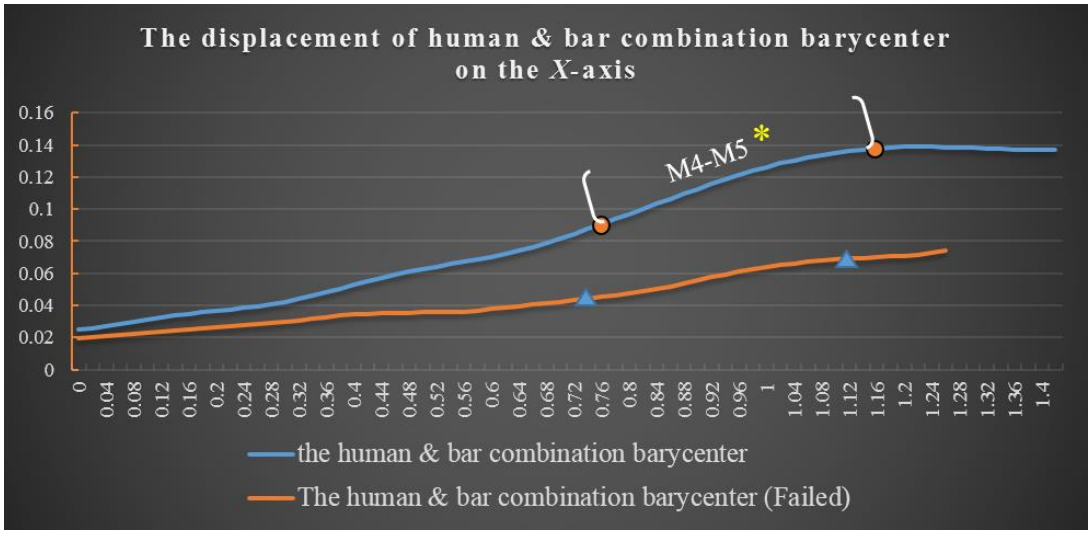

Figure 22 The displacement changes of human & bar combination barycenter of successful and failed snatch on the *X*-axis. *p<0.05, statistically significant difference.

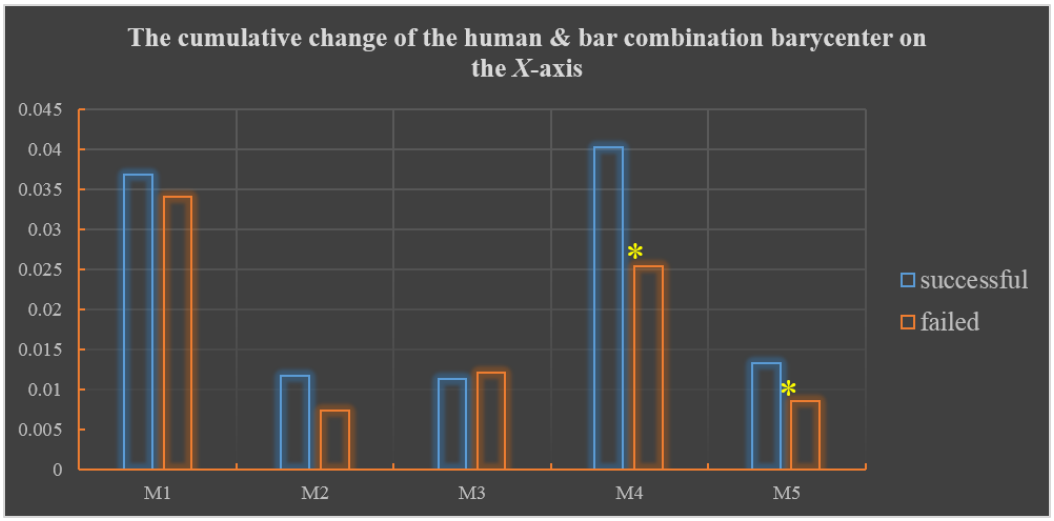

Figure 23 The cumulative changes of the human & bar combination barycenter of successful and failed snatch in *M*1-*M*5 on the *X*-axis. *p<0.05, statistically significant difference.

Related articles to the 2nd thesis point:

[1] Sun Xiaoyu, Pan Huiju, **Liu Gongju**, Zheng Zhe, (2020). A study on the causes of snatch failure based on the relationship between body-barbell resultant gravity center and bearing surface center. *Zhejiang Sport Science*, 42(2), 107-112.

[2] Zhu Houwei, Shi Shusheng, Shen Cuimei, **Liu Gongju**, Pan Huiju, (2019). A biomechanical study on the failure of snatch in high-level athletes based on the human & bar combination barycenter. *China Sport Science and Technology*, 55(9)39-46.

3rd Thesis point: Patella tendinopathy is currently widespread in my athletes, and it is one of the important factors hindering the improvement of athletes' performance, which seriously affecting training and competition. In my thesis, I experimentally determined on professional, active athletes that Extracorporeal Shockwave Therapy (ESWT), combined with rest, can effectively improve the morphology of patella tendon, since the five main properties (proximal-, distal thickness, longitudinal length, hypo-echogenic, and calcifications zones) were significantly reduced. Due to this applied therapy, more than 90% of the athletes who participated in the study could return to their professional sport carrier. (Figure 15, Figure 16, Figure 17, and Figure 18). Therefore, ESWT combined with rest can effectively treat patella tendinopathy, and musculoskeletal ultrasound can accurately monitor the treatment effect. Due to this applied therapy, more than 90% of the athletes who participated in my study not only could return to their professional sport carrier, but also many of them achieved excellent results.

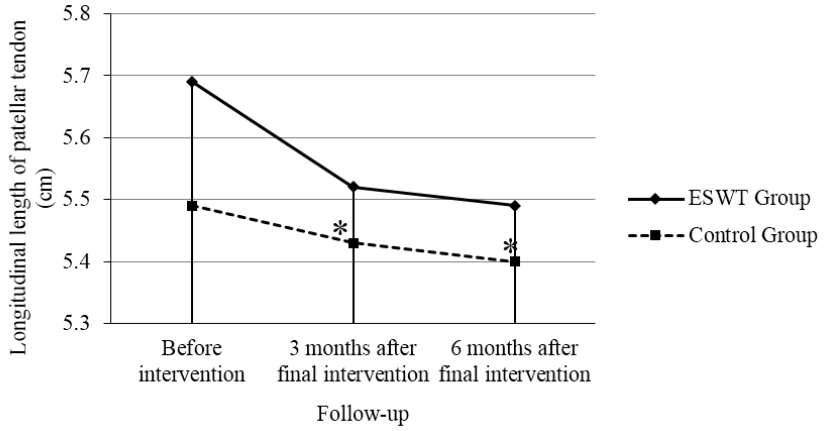

Figure 15 Comparison of changes between ESWT and control groups in longitudinal length of patellar tendon. *p<0.05, statistically significant difference between before and after intervention of the same group.

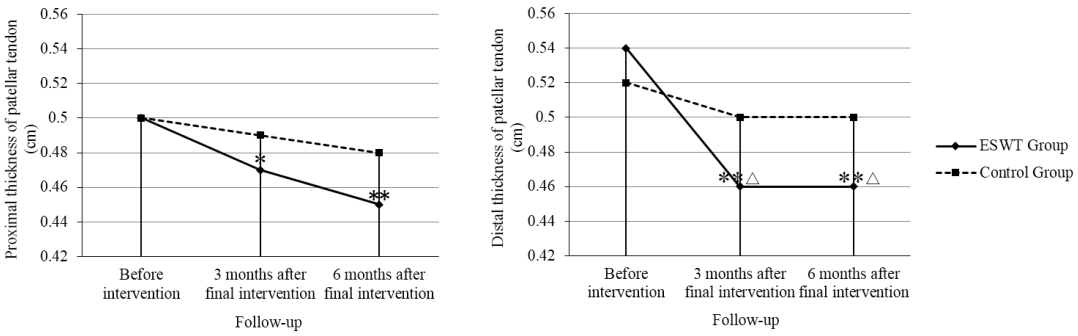

Figure 16 Comparison of changes between ESWT and control groups in thickness of patellar tendon. *p<0.05, **p<0.01, statistically significant difference between before and after intervention of the same group. △p<0.05, statistically significant difference between the ESWT group and the control group.

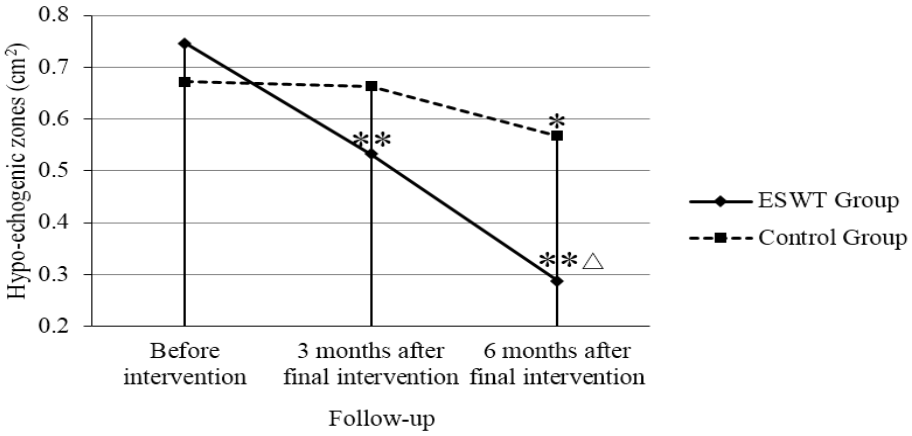

Figure 17 Comparison of changes between ESWT and control groups in hypo-echogenic zones. *p<0.05, **p<0.01, statistically significant difference between before and after intervention of the same group. △p<0.05, statistically significant difference between the ESWT group and the control group.

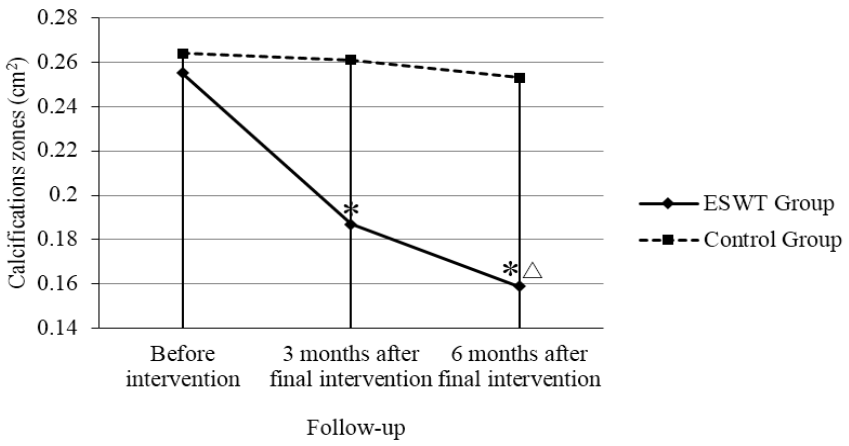

Figure 18 Comparison of changes between ESWT and control groups in calcifications zones. *p<0.05, statistically significant difference between before and after intervention of the same group. $^{\triangle}p$<0.05, statistically significant difference between the ESWT group and the control group.

Related articles to the 3rd thesis point:

Liu Gongju, Jing Ma, Yichao Ji, Hongchun Yang, Gusztáv Fekete, (2019). Ultrasonic image changes of extracorporeal shockwave therapy for patellar tendinopathy in Chinese professional athletes. *Journal of Medical Imaging and Health Informatics*, 9(3), 566-572. **IF: 0.499, Q4**

List of publications and scientific research achievements

Scientific publications in international journals:

1. **Liu Gongju**, Gusztáv Fekete, Hongchun Yang, Jing Ma, Dong Sun, Qichang Mei, Yaodong Gu, (2018). Comparative 3-dimensional kinematic analysis of snatch technique between top-elite and sub-elite male weightlifters in 69-kg category. *Heliyon*, 4(7), e00658, **Q1**
2. **Liu Gongju**, Jing Ma, Yichao Ji, Hongchun Yang, Gusztáv Fekete, (2019). Ultrasonic image changes of extracorporeal shockwave therapy for patellar tendinopathy in Chinese professional athletes. *Journal of Medical Imaging and Health Informatics*, 9(3), 566-572. **IF: 0.499, Q4**
3. Liu Yuwei, Chen Feifei, **Liu Gongju**, Liang Zhiqiang, Popik Sergey, Lian Wenlan, (2020). Moxibustion intervention effect to vertical jump performance. *Journal of Medical Imaging and Health Informatics*, 10(5), 1171-1177. **IF: 0.499, Q4**
4. Wenjing Quan, Meizi Wang, **Liu Gongju**, Gusztáv Fekete, Julien S Baker, Feng Ren, Yaodong Gu, (2020). Comparative analysis of lower limb kinematics between the initial and terminal phase of 5km treadmill running. *Journal of Visualized Experiments*, **IF: 1.300, Q3**
5. Fekete, G., Sun, D., **Liu Gongju**, Gu, Y. D., Balassa, G. P., Bíró, I., ... & Jánosi, E. (2018). Preliminary Results of Size and Slide-Roll Effect on the Kinematics of Total Knee Replacements. *Acta Polytechnica Hungarica*, 15(6), 143-153. **IF: 1.286, Q3**

Scientific publications in Chinese journals:

1. **Liu Gongju**, Li Jianshe, Pan Huiju, (2019). Critical technique characteristics of snatch at nearly extreme mass of Olympic champions. *Journal of Beijing Sport University*, 42(9), 127-136.
2. **Liu Gongju**, Yu Jinxing, Hu Ting, Ying Chunyi, Pan Huiju, (2019). Study on the effect of "warm-up" for the Functional Movement Screen™ (FMS™) in predicting sport injury risk. *Zhejiang Sport Science*, 41(2), 92-97.
3. **Liu Gongju**, Bi Zhiyuan, Hu ting, (2015). Speed indicators analysis on the snatch in Chinese Male's small levels (56 to 77 kg class) weightlifting athletes. *Zhejiang Sport Science*, 37(5), 125-128.
4. **Liu Gongju**, Fang Haibo, Hu ting, Ying Chunyi, (2014). The optimization analysis on Chinese excellent women's double kayak sprint. *Zhejiang Sport Science*, 36(5), 105-108.
5. Wu Ziying, Li Jianshe, **Liu Gongju**, Ying Shanshan, Shao Guoqiang, (2021), Biomechanical analysis of key points in typical techniques of squat clean and jerk of Li Dayin and Lyu Xiaojun. *China Sport Science and Technology*, 57(1), 58-65.
6. Dan Linfei, Wu Ziying, Shi Zhiyong, Mei Qichang, **Liu Gongju**, Li Jianshe, (2021), The kinematics analysis of the key technique of the classic women's split jerk-Based on the technical diagnosis of Liao Qiuyun's breaking the world record in clean and jerk at the World Championship. *Zhejiang Sport Science*, 43(2), 96-103.
7. Ma Jing, Gong Zaifeng, Li Hang, **Liu Gongju**, (2021). Analysis of the characteristics of biochemical indexes of Zhejiang youth men's volleyball athletes before key games. *Zhejiang Sport Science*, 43(1), 95-100.
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6. Ying Chunyi, **Liu Gongju**, Ma Jing, Pan Huiju. Study on the effect of "warm-up" for the Functional Movement Screen in predicting sport injury risk. *Chinese Association of Biomechanics in Sports (CSSB) 2018*. At Lanzhou, China.

The main achievement of my athletes in international competitions:

1. 2016 Rio Brazil Olympic Games, the men's weightlifting 69kg category gold medal (snatch 162kg, clean and jerk 190kg, total result 352kg).
2. 2018 Ashgabat Turkmenistan World Championships, the men's 73kg category gold medal, and broke the world records of snatch, clean and jerk and total score (snatch 164kg, clean and jerk 196kg, total result 360kg)
3. 2018 Ningbo China Asian Championships, the men's 73kg category gold medal, and broke the world record of snatch and total result (snatch 168kg, clean and jerk 194kg, total result 362kg)
4. 2019 Pattaya Thailand World Championships, the men's 73 kg category gold medal, and broke the world record of clean and jerk and total result (snatch 166kg, clean and jerk 197kg, total result 363kg)
5. 2019 Tianjin China World Cup, the men's 73kg category gold medal, and broke the world record of clean and jerk(snatch 165kg, clean and jerk 198kg, total result 363kg)
6. 2021 Tokyo Japan Olympic Games, the men’s weightlifting 73kg category gold medal, and broke the world record of clean and jerk and total result (snatch 166kg, clean and jerk 198kg, total result 364kg)
7. 2021 Tokyo Japan Olympic Games, Badminton Mixed Doubles gold medal and silver medal.
8. 2021 Tokyo Japan Olympic Games, Badminton women’s singles gold medal.

Scientific research projects related to the thesis:

1. **Liu Gongju**, Zhu Houwei, Hu Ting, Bi Zhiyuan, et al., (2020). Technology support service on the key weightlifting techniques of Shi Zhiyong prepares for Olympic Games. From: General Administration of Sport of China.
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