A BIOMECHANICAL ANALYSIS OF THE KNEE JOINT DURING POWER CLEAN

by

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LIST OF ABBREVATIONS

1-RM	1 Repetition Maximum
2D	Two-Dimensional Kinematic Analysis
3D	Three-Dimensional Motion Capture Analysis
ESS	Exercise and Sport Science
IWF	International Weightlifting Federation
JRF	Joint Reaction Force
MSN	Majlis Sukan Negeri
QTM	Qualysis Track Motion Software
ROM	Range of Motion
SPSS	Statistical Product and Services Solutions
USM	Universiti Sains Malaysia
USSR	Union of Soviet Socialist Republic

ANALISIS BIOMEKANIK UNTUK SENDI LUTUT SEMASA 'POWER CLEAN'

ABSTRAK

PENGENALAN: Sehingga kini, analisis biomekanik terhadap bahagian atas badan semasa acara 'clean and jerk' untuk menganalisi pergerakan anggota bahagian atas badan dan mengurangkan risiko kecederaan telah dijalankan. Walaubagaimanapun, analisis biomekanik terhadap bahagian bawah badan (sendi lutut) semasa acara 'clean and jerk' bagi atlet angkat berat lelaki dan perempuan peringkat negeri amat sedikit diketahui. **TUJUAN:** Kajian ini telah dijalankan untuk membandingkan pelbagai gerakan sendi lutut mengikut 1 pengulangan maksimum (1-RM) dan 50% daripada 1-RM, untuk membandingkan pecutan barbell mengikut 1-RM dan 50% daripada 1-RM dan untuk mengukur dan menganalisi daya tindak balas sendi lutut mengikut 1-RM dan 50% daripada 1-RM. **KAEDAH:** Dua puluh lima atlet angkat berat terbaik peringkat negeri (17 lelaki dan 8 perempuan) menawarkan diri untuk mengambil bahagian dalam kajian ini. Analisis biomekanik termasuk dua dimensi (2D) analisis kinematik dan tiga dimensi (3D) analisis kinematik menangkap gerakan. Untuk analisis 2D, para peserta telah diberi galakkan untuk melaksanakan 1-RM 'power clean' dan prestasi peserta telah direkod menggunakan kamera video. Sementara itu, untuk uijan analisis 3D, ujian 'power clean' pada 50% daripada 1-RM dicatatkan menggunakan kamera menangkap gerakan kelajuan tinggi. **KEPUTUSAN:** Hasil kajian ini menunjukkan bahawa nilai min pelbagai gerakan (ROM) sendi lutut dan pecutan barbell pada 50% daripada 1-RM 'power clean' lebih tinggi berbanding pada 1-RM 'power clean'. Kedua-dua parameter tersebut merupakan statistik signifikan ($p<0.05$) diantara 1-RM dan 50% daripada 1-RM

‘power clean’. Daya tindak balas (JRF) sendi lutut pula telah menunjukkan data yang tidak seimbang kerana jurang bilangan yang besar antara atlet angkat berat lelaki dan perempuan. Oleh itu, hanya data deskriptif telah ditunjukkan. **PERBINCANGAN:** Berdasarkan keputusan, data demografi menunjukkan penilaian fizikal keseluruhan atlet berada dalam kategori wajar. Selain itu, nilai pelbagai gerakan sendi lutut semasa 50% daripada 1-RM dan 1-RM ‘power clean’ adalah lebih rendah daripada julat normal. Kemudian, perubahan pecutan barbell terjejas oleh intensiti latihan. Tambahan pula, nilai daya tindak balas sendi lutut semasa fasa tarik kedua dikalangan lelaki dan perempuan tidak berada di dalam julat normal.

A BIOMECHANICAL ANALYSIS OF THE KNEE JOINT DURING POWER CLEAN

ABSTRACT

INTRODUCTION: To date, the biomechanical analysis of upper limb during clean and jerk event for analyzing the movement of the upper limb and reducing the risk of injury have been on-going being investigated. However, little is known about the biomechanical analysis of lower limb (knee joint) during clean and jerk event in young males and females best state-level weightlifters. **PURPOSE:** This study was carried out to compare the knee joint range of motion following 1 Repitition Maximum (1-RM) and 50% of 1-RM power clean, to compare the barbell acceleration following 1-RM and 50% of 1-RM power clean at the second pull phase and to measure and analyse the knee joint reaction force during 50% of 1-RM power clean weightlifting. **METHOD:** Twenty-five best state-level weightlifters (17 males and 8 females) volunteered to participate in this study. The biomechanical analysis was included the two-dimension (2D) kinematic analysis and three-dimension (3D) motion capture analysis. For 2D analysis test, the participants were encouraged to perform 1 Repetition Maximum (1-RM) power clean and the performances of the participants were recorded using the video camera. Meanwhile, for 3D analysis test, the power clean test at 50% of 1-RM was recorded using high speed motion capture cameras. **RESULT**: The result of this study indicated that the mean value of the knee joint range of motion (ROM) and barbell acceleration at 50% of 1-RM power clean were greater compared to at 1-RM power clean. Both parameters were statistically significant ($p<0.05$) between 1-RM and 50% 1-RM power clean. The knee joint reaction force (JRF) data were not comparable due to huge gap of the number of male and female weightlifters. Therefore, only the descriptive data were shown. **DISCUSSION:** Based on the result, the demographic data showed the overall physical evaluation of the athletes, which was in fair category. Moreover, the values of the knee joint range of motion during 50% of 1-RM and 1-RM power clean were lower than the normal range. Then, The change of the barbell acceleration was affected by the intensity of the training. Furthermore, the value of the knee joint reaction force during the second pull phase among male and female was not in the normal range. In conclusion, two-dimensional kinematic analysis was able to explore the power clean technique while the three-dimensional motion capture analysis was able to investigate the mechanical principles of power clean.

CHAPTER 1

INTRODUCTION

1.1 Background

Weightlifting is a strength sport that requires exceptional power, speed of movement and flexibility. Weightlifting also has been a longstanding part of the modern Olympic Games and has wide and growing international participation (Storey and Smith, 2012). In the performance of the competitive lifts, weightlifters are required to generate extremely high peak forces and contractile rates of force development and, consequently, high peak power outputs and contractile impulses (Storey et. al, 2012). According to Lester and colleagues (2014), there are two major lifts involved in competition: the snatch (a barbell is lifted overhead in one singular movement); and the clean and jerk (the barbell is lifted to shoulders initially and a secondary movement is used to displace the barbell overhead).

Based on Storey and Smith (2012), the clean and jerk event has two-part lift. They observed that the weightlifters are able lift heavier loads (18-20% greater) during clean and jerk compared to the snatch. Furthermore, they noted that the clean requires the barbell to be raised from the floor (using a shoulder width grip) to the front of the shoulders in one continuous movement. Storey and Smith (2012) also found that there are six phases in the clean which are the first three phases (first pull, transition or double knee bend and second pull) are the same as those of the snatch and the second three phases (catch, downward movement phase and recovery) are different compared to the snatch. Next, as the barbell rise in the vertical plane to approximately 55–65% of the lifter's height (Drechsler, 1998) the lifter initiates the 'turnover' phase. The lifter then 'catches' the barbell on their shoulders and descends into a full squat position. The lifter then recovers from the full squat position to prepare for the jerk.

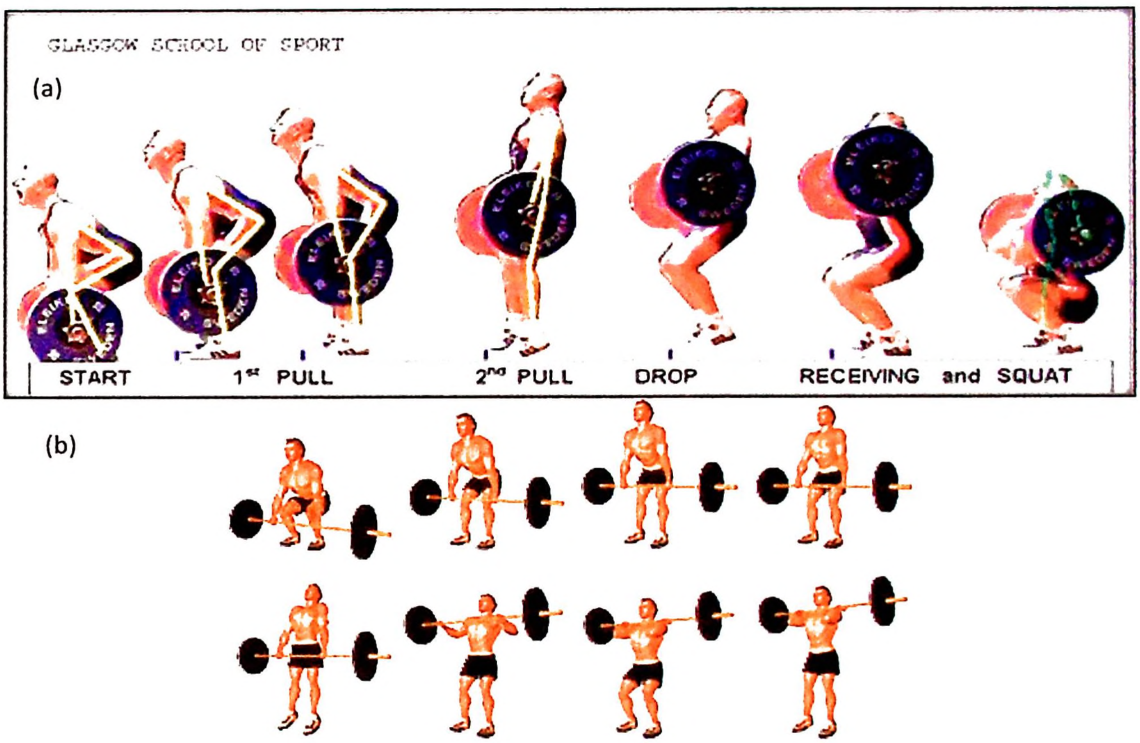

Figure 1.1 (a) Clean Technique; (b) Power Clean Technique

Furthermore, the jerk also has six phases (start. dip, jerk drive, unsupported split under the bar, supported split under the bar, recovery). First, the lifter and the barbell must become motionless. Then, the lifters begin to dip down by flexing at the knee and hip, with the barbell held across the shoulders. At the bottom point of the dip, the lifter makes the transition to the jerk drive where they are required to accelerate the barbell in the vertical plane. During this transition period, the athlete may be exposed to a downward force equivalent to 17 times their body mass (Zernicke et. al, 1977). At the completion of the jerk drive, the barbell is vertically driven off the shoulders and the lifter's feet leave the ground. This phase represents the fourth phases (unsupported split under the bar). Once the lifter's feet are in contact with the ground and the barbell is held overhead with fully extended arms, the lifter is in the fifth phases (supported split under the bar). Finally, the lifter must then recover and is required to stand motionless with their feet parallel to one another. The duration of effort from the start of the first pull to the signal of a successful lift is ~8–12 seconds.

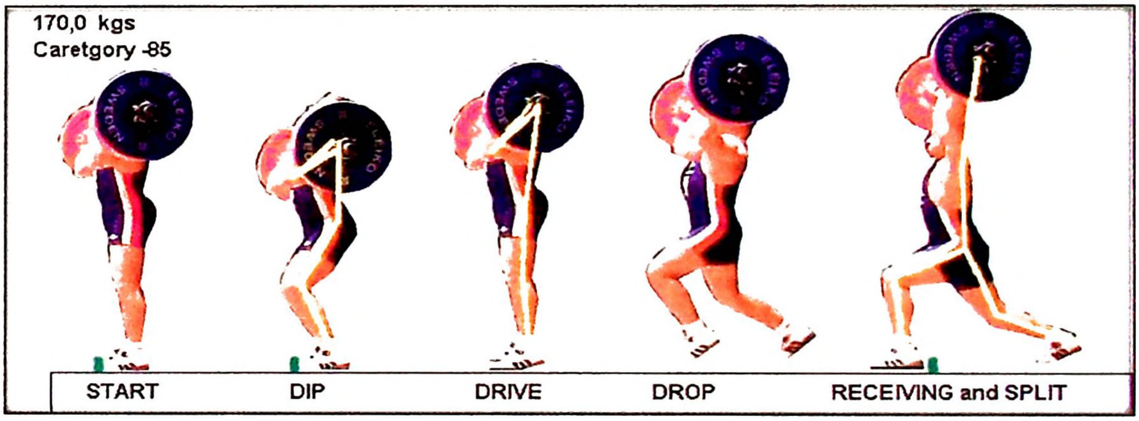

Figure 1.2 Jerking Technique

Nowadays, the power clean is the best technique in developing power in strength and conditioning programs. However, in recent times, the power clean is rarely implemented other than a gym specializing in Olympic weightlifting (Heffernan, 2011). Power clean utilizes the triple extension movement of the hip, knee, and ankle joint which is the movement pattern found in jumping (basketball), tackling (football) and the start of a sprint (athletic) (Tucker, n.d.). The triple extension movement in the power clean promotes the development of power by moving heavy weight at rapid speeds (acceleration). The equipment of the power clean is similar as classic clean: a regular straight bar (for novice athletes) and an Olympic bar (if the lifters ready to handle 20 kilograms and above).

Besides, the power clean has six phases similar as the classic clean (first pull, transition scoop, second pull, catch, downward movement phase and recovery. Nevertheless, there are slightly differences between classic clean (applied in any competitions) and power clean (mostly applied in strength and power training). One of differences between two lifting is at the fourth phases when the lifter catches the barbell after the phase of second pull. In classic clean, the lifter catches the barbell on their shoulder and descends into the full squat position but the lifter descends into the standing position during a power clean.

Figure 1.3 Full Squat Position

In weightlifting, the knee is one of the important joint during the kinetic chain of lifting. Major lower limb joint utilized in all phases of lifting. The rapid speeds in weightlifting is important especially from the phase of second pull to the catch phase. In addition, the knee need to bear the weights of the barbell at the same time the full of knee flexion. The position increases the stress load on the knee joint and causes it to be proned to injuries such as the tearing of ligaments (anterior cruciate ligament, medial cruciate ligament or posterior cruciate ligament) and patellafemoral maltracking (a shifting of the patella). Based on Calhoon et. al (1999), knee tendinitis, especially patellar tendinitis, is a problem for many athletes, and high knee forces during weightlifting movements are typical. It is thus believed that the correction of the clean and jerk techniques can help to boost performance.

Today, weightlifting is considered one of the most popular strength and power sport in Malaysia. Hence, there is a need to give some attention in this sport. Weightlifting sport in Malaysia has been developed for a few decades using traditional training method. However, the scientific study and information about weightlifting are still lacking. The biomechanics analysis is not very well implemented in Malaysia. In biomechanical analysis, the false technique of lifting and the mechanical power can be found. Moreover, the biomechanical analysis is important in various sports either endurance sport or strength and power sport. In order to improve the level of competitiveness of Malaysian Weightlifter in world classed competition, it is necessary to approach the training method scientifically especially in the biomechanics aspect. The recent researchers are implemented the biomechanical analysis in their study by determining the exact effects of the increased barbell weight on the barbell and body kinematics might help to understand the effective technical factors and the biomechanics of successful lifts of higher weights (Hadi et. al, 2012).

Since no study has been undertaken to determine a biomechanical analysis of the knee joint during clean and jerk event in group male and female with the age ranging from 13-18 years old, the present study was proposed.

1.2 Objectives of the Study:

This study embarks on the following objectives:

1) To compare the knee joint range of motion following 1-RM and 50% of 1-RM power clean.
2) To compare the barbell acceleration following 1-RM and 50% of 1-RM power clean at the second pull phase.
3) To measure and analyse the knee joint reaction force during 50% of 1-RM power clean weightlifting.

1.3 Significance of the Study:

The study was focused on the biomechanics of the knee joint, which is one of the most frequently injured joint among athletes involved with weightlifting. The results of this study were expected to improve the power clean technique and reduce the risk of knee joints injuries.

1.4 Hypothesis:

Null Hypothesis:

1. There is no difference of the range of motion of the knee joint during 1-RM and 50% of 1-RM power clean.
2. There is no difference of the barbell acceleration during 1-RM and 50% 1-RM power clean
3. There is no difference of the knee joint reaction force between male and female weightlifters during 50% 1-RM of power clean.

Alternate hypothesis:

1. There is difference of the range of motion of the knee joint during 1-RM and 50% 1-RM power clean.
2. There is difference of the barbell acceleration during 1-RM and 50% of 1-RM power clean.
3. There is difference of the knee joint reaction force between male and female weightlifters during 50% of 1-RM power clean.

1.5 Operational Definitions:

Power clean: The prefix of power simply means that the weightlifter was going to land in the partial squat (standing squat). There were 6 phases completed by the weightlifters; the first pull, transition, the second pull, the catch, the downward movement phase and the recovery.

2-Dimension (2D) Kinematic: For 2D kinematic, the analysis was carried out for one day or one session only. The lifters were required to complete lift with 100% of perceived maximum resistance.

3-Dimension (3D) Kinematic: For 3D kinematic, the analysis was carried out for one session only. The lifters were attached with the markers (lower limb only) and they were required to complete lift 50% of 1 Repetition Maximum.

Young male and female subjects: A group of male and female best-state level weightlifters from Majlis Sukan Negeri Kelantan aged 13 to 18 years old were recruited.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction of Weightlifting

Weightlifting is a sport in which success is overwhelmingly dependent upon the abilities of its participants to generate prodigious amount of power. According to Chiu et al., (2010) Olympic weightlifting is a sporting event that requires high technique and stability. Okada et. al (2008) said, in weightlifting competitions, weightlifters compete on combined (total) weight for the clean and the snatch. The competitions are about an essential skill is to transmit physical output effectively to the barbell and support the barbell over the head. As the result of the skill, weightlifters are successful in a lift of the clean and jerk or the snatch. Furthermore, in a real competition, a failed attempt usually occurs when the barbell falls in front of or behind the weightlifter during the catch phase because of an incorrect amount of pull force or a poor catching technique (Chiu et al., 2010). Thus, weightlifting is the power sport that required high levels of physical ability and skill together.

2.2 History of Weightlifting

Weightlifting has been contested in each renewal of the modern Olympiad, it was not until 1920 that the competitive program was standardized by the International Weightlifting Federation (IWF), the governing body of sport (Takano, 1993). But, Lester et. al (2014) found that the first competition of weightlifting has been introduced in the Olympic Games in 1896. The snatch and the clean and jerk are two major lifts involved in competition. Moreover, Hoover et al., (2006) noted that weightlifting, an event restricted only to men in the past, has gained popularity among women since the first Women's World Weightlifting Championships in 1987, yet the performance development in this event has not been studied as much in women weightlifters as in men. In brief, weightlifting has been introduced since in Ancient Olympic Games and continue compete in Modern Olympic Games until now by involving two major lifts: the snatch and the clean and jerk.

According to Chiu, (2009) as of 2007, 167 countries are recognized by the International Weightlifting Federation. In the early part of the 20th century, the dominant nation in weightlifting was the United States. He also stated that from the 1950s to the 1970s, the Union of Soviet Socialist Republic (USSR) was the most successful country. However, between the 1970s and 1992, the USSR and Bulgaria shared the dominant position in weightlifting. After the dissolution of the Soviet Union in 1991, the number of elite competitors competing at international competitions increased, as many of the 15 former Soviet republics entered teams. Besides, since 1996, China has also competed for top position, and recently, nations in the Middle East and South America have fielded competitive teams. For the female weightlifting competition, The 1987 World Weightlifting Championship was the first such event in which female weightlifters participated as competitors (Gourgoulis et al., 2002). In Olympic Games, Not until the 2000 Olympic Games in Sydney did female weightlifters contest the snatch and clean and jerk at an Olympic event (Hoover et al., 2006). Thus, there are many countries participating in weightlifting competition and not only men as competitor, but also women joining weightlifting competition.

2.3 Types of Event in Weightlifting

There are two major lifts involved in weightlifting: the snatch and the clean and jerk. The snatch is a barbell is lifted overhead in 1 singular movement while the clean and jerk is the barbell is lifted to shoulder initially and a secondary movement is used to displace the barbell overhead (Lester et al., 2014). Moreover, Takano & Nuys, (1987) stated that the clean and jerk is the event in which an athlete can lift the greatest weight from the floor to overhead. Despite that, impact of clean and jerk weightlifting is a result of the feet returning to the ground after a momentary separation and receiving the barbell on the shoulders or overhead which occurs when the feet contact the ground (Moolyk et al., 2013). Thus, the snatch and the clean and jerk lifts involve very high mechanical power outputs from weightlifters (Garhammer, 1993).

2.4 Techniques of Power Clean

Rucci and Tomporowski, (2010) were described regarding to movement aspects present in all phase of the hang power clean. First, movement aspects present in the start phase of the hang power clean include (1) torso inclination relative to the ground, (2) distance ears are in front of the bar, and (3) position of bar relative to toe. Second, Movement aspects present in the pull phase of the hang power clean include (1) angle of body relative to ground in full extension, (2) position of bar relative to toe in full extension, and (3) time heels are out of contact with the floor. Finally, movement aspects present in the catch phase of the hang power clean include (1) time of elbow rotation under the bar, (2) knee angle, and (3) center of hip joint relative to toe. In summary, three of movement aspects present are important in all phase of the hang power clean.

According to Bob Tokano, (1987), there are several techniques of clean and jerk. First, in the power clean, the technique (1) begin with bar on the floor and hands closer together than before, (2) extending the legs only and lift the bar to the knees, (3) beginning the power position, with the body weight shifted forward, (4) balance on the metatarsals for a dynamic lift, (5) rack and catch and descend into front squat to complete the movement. Second, in the split jerk, the technique begin with right after the power clean techniques complete, (1) the starting position for jerk balance is the lead foot should be about 30 centimeters in front of the back foot, (2) the dip stage of the jerk balance. From here, the athlete drives the bar overhead and finishes by moving the feet further apart, (3) in the finish, the hands move from a clean width to a snatch width, reducing the height that the bar must be driven. In brief, there are many techniques in the clean and jerk event.

2.5 Musculoskeletal Injury in Weightlifting

Safety is a growing concern due to weightlifting becomes increasing popular (Hamill, 1994). This is because the lifts in the sport of weightlifting lifting emphasize explosive muscular power (Stone et al., 1994) that more tend to injury. Besides, they added that injuries in weightlifting have been reported to include not only soft tissue muscle injuries, but also condition such as spondylolysis and meniscal injuries. Additionally, Stone et al., (1994) again said in their study that most injuries occur at the knee, followed by the shoulder and the back and all the injuries are occur in the clean and jerk lift in weightlifting (Kulund et al., 1978). Calhoon and Fry, (1999) found that the most commonly injured sites include the back, knee and shoulder and that most of the injuries can be described as either acute or chronic rather than recurring or due to complications and consisted primarily of strains, tendinitis, and sprains. In brief, injuries always concern those in athletics, and weightlifting is no exception (Calhoon and Fry, 1999)

2.5.1 Common Injuries in Weightlifting

There are three anatomical areas thought to be at high risk of injury for weightlifting is also common injury sites in many sport (Mazur et al., 1993). First, one of the anatomical areas thought to be at high risk for weightlifting is knee injuries. Knee injuries are not only concern in the sport of weightlifting, but all athletes in general (Calhoon and Fry, 1999). One of problem for many athletes is knee tendinitis especially patellar tendinitis (DeHaven and Lintner, 1986) and high knee forces during weightlifting movements are typical (Calhoon and Fry, 1999). Furthermore, weightlifter is at high patellofemoral osteoarthritis (Kujala et al., 1995). Despite, the knee is a common site of injury in other activities, the occurrence of severe or joint integrity injuries is not common in weightlifting (Hamill, 1994). Based on study of Calhoon and Fry, (1999), I can conclude that knee injuries in weightlifting are mainly chronic inflammatory problems and not the traumatic stability problems.

Second, the anatomical area thought to be at high risk of injury for weightlifting is back problems. Based on Granhed and Morelli, (1988), back problems associated with both work and play are prevalent in our society. Spondylolysis is one commonly cited injury, a degenerative condition where the vertebrae develop stress fractures (Neviaser, 1991) and lead to much more serious problem of the fractured vertebra sliding forward (spondylolisthesis). Mundt et al., (1993) suggest that weightlifting may predispose athlete to spondylolysis. Rossi and Dragoni, (1994) reported spondylolysis which has been observed in 3% to 7% of the sports and general populations. One of the causes of back problems is activities incorporating alternating flexion and extension of the lumbar area creates a greater risk than those requiring compressive loading (Granhed and Morelli, 1988). Besides, during the execution of the pressing phase of the lift, extremely lordotic positions could occur while the athlete was holding very heavy weights overhead (Calhoon and Fry, 1999). Therefore, back problems are one of the anatomical areas thought to be at high risk of injury for weightlifting.

Third, the anatomical area thought to be at high risk of injury for weightlifting is the shoulder. This is because of its anatomical structure, flexing the shoulder into an extreme overhead position increases the risk of injury (Gross et al., 1993). Missed lifts sometimes involve dropping the weight behind the lifter in weightlifting is one of the causes of the shoulder injury. Based on Kulund et al., (1978), there is such a motion results in extreme external rotation and flexion of the shoulders. At the same time, this places the shoulder in a vulnerable situation and may increase the rate of shoulder injury (Mazur et al., 1993). Of course, the skill, flexibility, and strength of the weightlifter may help to prevent many of the problems that could affect the shoulder (Goertzen et al., 1989). Moreover, the shoulder is prone to strains as well as instability from the dynamic power movements and the techniques used in weightlifting (Kulund et.al 1978). Hence, anatomical shoulder stabilization is critical for the throwing athlete (DeHaven and Lintner, 1988). Heavy weight lifted in the at-risk position (as example, extreme flexion and abduction) place the connective structures of the shoulder at an increased risk of injury (Neviaser, 1991) is the other causes of the shoulder injury. In brief, the shoulder accounted for the most injuries in weightlifting (Gross et al., 1993).

As conclusion, the actual injury rate for the sport of weightlifting is comparable with many other sports and activities, (Rothenberger et al., 1988) indicating that training for this sport presents no greater risk of injury than other popular sports (Calhoon and Fry, 1999).

2.6 Biomechanical Analysis in Weightlifting

Most previous studies analyzed the kinematics of the lower limb joints to provide information on successful or unsuccessful lifts (Baumann et al., 1988). In weightlifting, the knee joint important for generating power to lift the loads. The knees execute a characteristic extension-flexion-extension movement, where the first knee extension is defined as the first pull, the knee flexion is defined as the transition from the first to the second pull, and the second knee extension is defined as the second pull (Garhammer, 1989). Thus, the knee extension and the knee flexion are required in the lifting movement of weightlifting.

2.6.1 Knee Flexion

In weightlifting, knee flexion angle was not different between the power clean and jump landing but greater in the drop landing and clean (Moolyk et al., 2013). However, all tasks required the leg to rotate forward at least 40-degree angle at peak knee flexion, and increasing leg forward rotation increases knee extensor net joint moment during squat activities (Chizewski and Chiu, 2012). Devita and Skelly, (1992) compared landings with greater and less than 90-degree angle of knee flexion. Moreover, they found that landings with greater knee flexion required more work to be performed at the knee.

In the comparison between women and men, women flexed their knees less and more slowly in the transition phase than men and that the drop under time during the turnover and catch phases was also longer in women (Gourgoulis et al., 2002). On the other hand, Bartonietz, (1996) proposed that taller weightlifters require a greater knee flexion angle to get into an optimal start position. Additionally, they reported that female weightlifters flexed their knees less and more slowly than men during the transition phase, in which elastic energy is stored, and they dropped under the barbell more slowly in the turnover and catch phases. In other studies, the transition phase is very critical and should be executed quickly with a small knee flexion to be effective (Gourgoulis et al., 2009). In summary, by comparing with men athletes, women athletes have less the knee flexion during transition phase.

2.6.2 Knee Extension

Furthermore, for the knee extension, The maximal extension velocity of the knees during the second pull was always greater than the corresponding velocity during the first pull, and during the second pull the maximal extension velocity of the hip was greater than the maximal extension velocity of the knees, giving an additional acceleration onto the barbell and contributing to the execution of an explosive second pull (Bauman et al., 1988). This allows the storage of elastic energy into the extensor muscles of the knees during the knees' flexion and its use during the following concentric contraction of the knees, resulting in an explosive power output during the second pull (Isaka et al., 1996). A common characteristic of the impact phase of jumping and weightlifting tasks is a large contribution of knee extensor work (Moolyk et al., 2013). At impact, the body possesses kinetic energy as a result of the conservation of energy from the initial drop height potential energy. After impact, work is performed using eccentric muscle loading to absorb this kinetic energy (Zhang et al., 2000). In weightlifting, a higher performance level can be achieved by decreasing the total work done and by more effectively utilizing the power-generating ability of the muscles (Hoover et al., 2006). Therefore, the knee extension has great relation with the knee flexion especially during lifting the loads.

2.6.3 Barbell Acceleration and Barbell Trajectory

Then, Winchester et al., (2005) stated that the velocity of the barbell and its trajectories is affected by changes in the external load. In calculation of barbell velocity via a linear position transducer, Thomas et al. (2007) used an inverse dynamics, while Kawamori et al. (2006) used a forward dynamics approach, but subtracted body weight from the vertical ground reaction force. However, for an effective lift, the vertical linear velocity of the barbell should be continuously increased until the end of the second pull, because the existence of 2 clear velocity peaks would demand additional energy from the lifter to overcome the negative momentum of the barbell during its velocity's decrease (Bartonietz, 1996). Moreover, the vertical variables of a barbell have often been used to evaluate the techniques of lifers (Hung-Ta et al., 2010). On the other hand, the velocity of the barbell and its trajectories are affected by changes in the external load (Kipp et al., 2011). Gourgoulis et al., (2002) found that maximum linear velocity of the barbell was greater in women than men might not be considered as an indicator of the better technique of women and should be attributed to the lesser load of barbell that women had to overcome. Thus, the barbell velocity is one of variables that affects by changes in the external load.

Again, Winchester et al., (2005) stated that the barbell trajectories are affected by changes in the external load. According to Gourgoulis et al., (2009), the barbell trajectories is when the bar is moved toward the lifter during the first pull and the transition phase, and during the second pull it is moved away from the lifter's body. Isaka et al., (1996) stated that the horizontal movement of the barbell during the pull phase should be considered an effective application of muscle power, and a small horizontal movement is necessary for good lifting technique. Besides, as the horizontal displacement of the bar increases during the lift, the lifter must exert more energy to control the loaded barbell (Hoover et al., 2006). In addition, the optimum trajectory is affected by relative body segment lengths and other leverage factors, such as muscle attachment points (Garhammer, 1985). However, Hoover et al., (2006) noted that the role that anthropometric factors play in the determination of the optimal barbell trajectory is unclear. As example, a gender-based difference was found in the horizontal movement of the barbell during the second pull: the barbell moved away from female lifters and crossed the vertical reference line, whereas it moved horizontally away from male lifters without crossing the vertical line (Gourgoulis et al., 2002). In another study, Hoover et al., (2006) stated that the barbell trajectory of female lifters was different from that of males, and an optimal toward-away-toward pattern was observed in less than half of the female lifters. Thus, in previous studies, an optimal barbell trajectory has been taken as an indicator of a mechanically effective pull and a proper technique (Bruenger et al., 2007).

Next, the horizontal displacement pattern of the barbell during the lift is also important (Stone et al., 1998) in that the horizontal movement during the first pull and transition phase allows the storage of elastic energy into the extensor muscles of the knees during the flexion of the knees and its use during the following concentric contraction of the knees, resulting in an explosive power output during the second pull (Gourgoulis, 2009). Then, Hoover et al., (2006) proposed that the horizontal displacement of the barbell is a toward-away- toward pattern: The barbell is pulled toward the body during the first pull and the transition phase, and, during the second pull, it moves away from the lifter's body, and finally, it drops toward the body from the maximum height. They added that the larger horizontal displacement of the barbell observed in women weightlifters in a national competition in 1999 was attributed to the weightlifters' inconsistency, and less than half of the snatch attempts demonstrated by the women weightlifters in that study displayed the optimal toward-away-toward horizontal bar trajectory. As example, Akkus, (2012) stated that the larger horizontal displacement of the barbell by women in the 69-kg category of the 1999 US Men's and Women's Weightlifting Championships was accounted for by the inconsistent or irregular displacement of the barbell, and less than half of the females' snatch attempts displayed the optimal toward-away-toward horizontal bar trajectory. In summary, the horizontal displacement is important during the first pull, transition phase and the second pull.

Moreover, Baumann et al., (1988) stated that lower extremity joint kinetics vary based on the external load. In the other study, the external load lifted during the pull phase of the clean has a direct influence on biomechanics of the lower extremity (Kipp et al., 2011). However, determining the exact effects of the increased barbell weight on the barbell and body kinematics might help to understand the effective technical factors and the biomechanics of successful lifts of higher weights (Hadi et al., 2012) besides, as the load of the barbell increased, decreases were found in the maximum vertical displacement of the barbell, the drop-under displacement, and the maximum vertical velocity of the barbell (Hoover et al., 2006). On the other hand, absolute magnitudes of joint power production differ to accommodate changes in external loads (Enoka, 1988). As example, in 1998 World Championship, women lifted greater loads and exerted more power in the second pull than men, but the duration of their second pull, their maximum vertical barbell velocity, and their maximum barbell height were lower (Garhammer, et al., 2001). Furthermore, as the load of the barbell increased, the drop-under time also increased, whereas the drop-under displacement, the maximum vertical displacement, and the maximum vertical velocity of the barbell decreased (Hoover et al., 2006). Thus, in weightlifting, load is an important variable that plays a determining role in the magnitudes of the vertical and horizontal kinematics of the barbell.

2.6.4 Mechanical Principles in Weightlifting

Besides, mechanical power was higher in the second pull compared with that in the first pull (Garhammer, 2001). Nevertheless, Gourgoulis et al., (2000) stated that the mechanical work and power outputs showed that the first pull was characterized by force, whereas the second pull was largely of power nature. Further, they also noted that the mechanical work during the first pull was higher than that of the second pull and that the vertical velocity of the barbell reached maximum levels during the second pull. Again, Gourgoulis et al., (2002) found that, the mechanical work done for the vertical displacement of the barbell in men was greater in the first pull than in the second pull, while it was found to be similar in both phases in women. By comparison of the gender, the mechanical work done by men to vertically displace the barbell was greater in the first pull than in the second pull and that the mechanical work done by women was similar in both phases (Akkus, 2012). In brief, the mechanical work is one of important variables in weightlifting.

2.7 Musculoskeletal Modeling

According to (Cleather and Bull, 2010), musculoskeletal modeling techniques can be used to analyze biomechanical problems where the direct measurement of key variables is difficult or impossible. Besides, they found that this requires a detailed description of the geometry of the musculoskeletal system to allow the calculation of muscle lines of action and moment arms.

3-dimensional kinematic (3D) and 2-dimensional kinematic (2D) are two types of biomechanical analysis. On the other hand, 3D also can use for musculoskeletal modeling. Based on Chiu et al., (2010), the 3-dimensional kinematic analysis is necessary to decrease the measurement errors that will occur in the 2-dimensional approach. The performance of a 3D model is highly influenced by the independence, variability, and number of moment arms (Cleather and Bull, 2010). He also reported that 3D model also can arrive at a solution with only a few muscle elements or one with a large number of muscle elements that is unable to arrive at a solution. However Hung-Ta et al., (2010) also found that 2D in the sagittal plane is appropriate for describing a barbell's movement in weightlifting. In brief, the number of two-dimensional (2D) and three-dimensional (3D) models (Feller et al., 2007) have been employed to study the patellofemoral joint contact force during movement, and the calculated forces range from 0.4 kN during walking (Brechter and Powers, 2002) to 6.0 kN when landing after a jump (Simpson et al., 1996).

2.7.1 Two-Dimensional Kinematic Analysis

According to Horn, (1975) in two dimensions (2D), two degrees of freedom are required to generate arbitrary positions in a given work space and one more is needed to control the orientation of the last link. Moreover, he stated that in two dimensions one clearly needs two degrees of freedom to reach an arbitrary point within a given work space. Again, he found that, a three-link device is a general-purpose two-dimensional device that can generate orientation as well. He also noted that the calculation of joint angles given desired position and orientation is vital if around or follow a given trajectory. Thus, the two dimension is two degrees of freedom clearly needs to reach and generate arbitrary positions in a given work space.

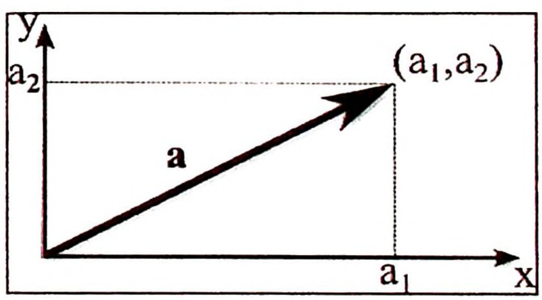

Figure 2.1 Two-Dimensional Axis