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# Mechanical Work Performed During Three Variations of the Clean

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## **Abstract**

The purpose of this research was to compare the work performed on the barbell and about the lower extremity joints during the propulsion phase of cleans performed with different objectives. Eight experienced weightlifters (2 females and 6 males) participated in two separate sessions. In session one, participants' one repetition maximum (1 RM) clean was determined. Concomitantly, technique was assessed using digital video; all participants demonstrated the towards-away-towards barbell trajectory. In session two, the participants performed cleans with sufficient effort to lift the barbell to 1) the minimum height required to receive it in a full squat (minimal height clean), or with maximum effort to elevate the barbell as high as possible and receiving it in a 2) full (maximal effort clean) or 3) partial (power clean) squat. Work performed on the barbell and about the lower extremity joints were computed from marker trajectories and ground reaction forces. Peak barbell height, total barbell work, total lower extremity net joint work, net knee extensor work, and net knee flexor work were smaller in the minimal height clean than the maximal effort and power cleans ( $P < 0.05$ ). Moreover, net ankle plantar flexor work was smaller in the minimal height clean than the power clean ( $P < 0.05$ ). The minimal height clean allowed the same barbell mass to be lifted by performing a smaller work on the barbell and about the lower extremity joints. The smaller net joint work performed during the minimal height clean was primarily accounted for by a smaller net knee extensor and flexor work.

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## Preface

Before you lay the master thesis entitled “Mechanical work performed during three variations of the clean exercise”. This thesis was undertaken to fulfill the graduation requirements of my Master of Science degree within the Department of Physical Performance at the Norwegian School of Sport Sciences. The research project was, however, conducted within the Faculty of Physical Education and Recreation at the University of Alberta during the fall of 2015, as part of a collaboration project between the two universities.

I came across the opportunity to conduct this project during a formal exchange at the University of Alberta the fall of 2014, where I took Dr. Loren Z. F. Chiu’s biomechanics course. As both Dr. Chiu and I have personal interest in the biomechanics of weightlifting, we started planning a research project for my thesis to be conducted at the University of Alberta. When I got home for the spring semester of 2015, Dr. Tron Krosshaug also caught interest in the project and over the semester he became increasingly involved in it. The process of conducting a research project across borders has been challenging, yet an incredible learning experience. Moreover, my thesis work has opened opportunities for future collaboration projects, as well as given me both academic and personal friends from many different places around the world.

I consider myself extremely lucky for being allowed to take part in this incredible experience, and would therefore like to thank some of the key actors making this project possible. First I want to thank my supervisors, Dr. Loren Z. F. Chiu and Dr. Tron Krosshaug, for their outstanding mentoring throughout my MS program. Further, I wish to thank Dana Dragon-Smith and Mette K. Oftebro for their efforts making my work across borders possible, and “Kjell Nordviks Fond” and “Advokat og Major Eckbos Legat” for providing me with financial support. Lastly, I would like to thank Amy Moolyk for assisting me in the process of recruiting participants, as well as the participants who volunteered to participate in my research study.

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## 1. Introduction

The sport of weightlifting was first introduced in its modern form during the 1800s, and interest in weightlifting has continued to increase over the last centuries (Urso, 2011). Moreover, the competition exercises, as well as variations of these, have been purported to increase performance in tasks requiring high rates of force development, such as jumping (Canavan, Garrett, & Armstrong, 1996; Chiu & Schilling, 2005; Garhammer & Gregor, 1992; Hori, Newton, Nosaka, & Stone, 2005). For this reason, the competition exercises in weightlifting are commonly implemented in strength and conditioning programs (Ebben & Blackard, 2001; Ebben, Carroll, & Simenz, 2004; Simenz, Dugan, & Ebben, 2005). Lately, the weightlifting exercises have also caught the attention of the commercial training market, and are now commonly used by recreationists at commercial training centers.

The two events contested in weightlifting are the snatch and clean & jerk (Garhammer, 1993; Isaka, Okada, & Funato, 1996). In the snatch, the athlete lifts the barbell from the ground to an overhead position with the arms fully extended, in one continuous movement (Garhammer, 1980; Isaka et al., 1996; Stone, Pierce, Sands, & Stone, 2006a). In the clean & jerk, the barbell is first lifted from the ground to the shoulders in one continuous movement during the clean (Stone et al., 2006a). Subsequently, the barbell is trusted overhead using the legs, and received on extended arms in the jerk (Stone et al., 2006a). Both the snatch and clean are initiated with a propulsion phase, known as the pull, where the barbell is lifted from the floor to approximately waist height (Enoka, 1979, 1988). The technique most commonly used to achieve this is the double knee bend technique, which includes a complex pattern of flexion/dorsi flexion and extension/plantar flexion of the hip, knee, and ankle (Baumann, Gross, Quade, Galbierz, & Schwirtz, 1988; Enoka, 1988; Häkkinen, Kauhanen, & Komi, 1984; Stone et al., 2006a). Moreover, this complex motion is executed with high movement velocities despite large external loads (Garhammer, 1980), rendering the competition lifts in weightlifting highly technically demanding (Enoka, 1988; Garhammer, 1979a). For this reason, a number of opinions on how these exercises should be performed in order to optimize weightlifting technique have emerged.

Although the snatch and clean display some general kinetic and kinematic characteristics, weightlifters may perform these exercises with different objectives. One aspect that may be varied is the effort the barbell is lifted with. For example, maximal effort can be exerted

during the propulsion phase to elevate the barbell as high as possible (Bartonietz, 1996; Hedrick, 2004; Takano, 1987a, 1987b). Subsequently, the barbell is received in a full (maximal effort snatch/clean) or partial (power snatch/clean) squat. Alternatively, the barbell can be raised to the minimum height required to successfully receive the barbell in a deep squat (minimal height snatch/clean) position (Derwin, 1990; Kipp & Harris, 2015). Naturally, one can argue that the differences between exerting maximal effort on the barbell and lifting the barbell to a minimal height will be minor if maximal loads are used. However, the majority of regular weightlifting training is performed with submaximal loads (Stone, Pierce, Sands, & Stone, 2006b).

The minimal height variation may be thought to resemble the technique of elite weightlifters, as they lift the barbell to a smaller peak height and with a smaller peak velocity than their less skilled counterparts (Baumann et al., 1988; Burdett, 1982; Garhammer, 1993; Häkkinen et al., 1984; Ikeda et al., 2012). Thus, it may be hypothesized that performing the minimal height variations at submaximal loads could be used to train aspects of the lifts that allow the barbell to be raised to a smaller peak height, such as a fast squat under the barbell (Burdett, 1982; Häkkinen et al., 1984; Kauhanen, Häkkinen, & Komi, 1984). On the other hand, it could also be hypothesized that exerting maximal effort during the pull would cause favourable muscular adaptations as the neuromuscular activation may be higher during these variations (Behm & Sale, 1993; Suchomel, Wright, Kernozek, & Kline, 2014). Despite this ambiguity, it does not appear to be any consensus as to which variation should be used in training. Since how the weightlifting exercises are specifically performed may alter the neuromuscular adaptations elicited in response to using these exercises in training, research studies investigating the effects of performing the snatch or clean with different effort are warranted.

Before commencing in such a comparison, the meaning of effort in this context should be elaborated on. Several authors advocating that maximal effort should be exerted on the barbell during the pull emphasize lifting the barbell as high as possible (Hedrick, 2004; Takano, 1987a, 1987b). Others have emphasized that the barbell should be lifted with maximal velocity (Bartonietz, 1996). Moreover, it is commonly recommended to use the power snatch, power clean, and other variations that emphasize these aspects (e.g. hang power clean, jump shrug and high pull) as progression steps when teaching the snatch and clean (Hedrick, 2004; Suchomel, Comfort, & Stone, 2015; Suchomel, DeWeese, Beckham, Serrano, & French, 2014; Suchomel, DeWeese, Beckham, Serrano, & Sole, 2014; Takano, 1987a, 1987b). Thus,

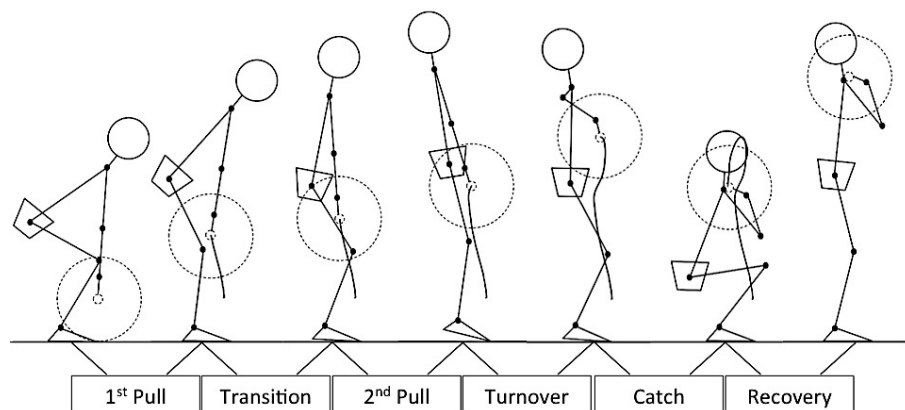
it appears that the goal of exerting maximal effort during the propulsion phase is to elevate the barbell to greatest height possible, or lifting it with the greatest velocity possible. In contrast, the notion of lifting the barbell to a minimum height has only been mentioned by a few authors (Derwin, 1990; Hadi, Akkus, & Harbili, 2012; Kipp & Harris, 2015). Nevertheless, the goal of this variation is to minimize the peak barbell height to what is strictly necessary to successfully complete the lift by avoiding exerting maximal effort during the propulsion phase (Derwin, 1990). In line with these previous publications, maximal effort will here be interpreted as the intent to lift the barbell as high as possible and with maximal velocity.



## 2. Theoretical Background

### 2.1 The Phases of The Lifts

For the purpose of analyzing the snatch and clean, these lifts may be divided into phases. As both exercises are similar in nature (Enoka, 1979), the same six phases are typically used for both the snatch and clean (Figure 2.1).



**Figure 2.1:** The clean may be divided into six phases based on seven different key positions. The barbell trajectory of the recovery phase is not shown in the figure, but may be expected to be close to vertical.

A lift starts when the barbell is accelerated vertically, causing the weight discs to separate from the surface on which they are resting. This instant is known as the lift-off, and initiates the first phase, known as the first pull (Gourgoulis, Aggeloussis, Garas, & Mavromatis, 2009). During this phase the knees and hips extend, while the ankles simultaneously plantar flex. The shoulders and hips rise at approximately the same velocity, causing the angle between the ground and a line projected between the shoulder and hip to remain close to constant throughout this phase (Garhammer, 1978; K. Kipp, J. Redden, M. B. Sabick, & C. Harris, 2012b). This allows the knees and barbell to move posteriorly during the first pull, a common feature of elite weightlifters' technique (Garhammer, 1985). The first pull ends when the knees reach their first maximal extension angle, just after the barbell has passed the knees (Baumann et al., 1988; Garhammer, 1978; Gourgoulis et al., 2009; Medvedev, 1988; Stone et al., 2006a).

The transition phase follows the first pull, and is initiated at the first maximal knee extension (Gourgoulis et al., 2009). During this phase the athlete repositions the torso to a more vertical position by flexing/dorsi flexing the knees and ankles, while simultaneously extending the hips (Garhammer, 1978). The repositioning of the torso facilitates a jumping like motion in the last phase of the pull (Bartonietz, 1996; Enoka, 1979, 1988; Garhammer, 1978, 1982; Stone et al., 2006a). The barbell continues to rise throughout this phase, which is completed when the knees reach their second maximal flexion angle (Bartonietz, 1996; Medvedev, 1988; Stone et al., 2006a).

The third phase is the second pull, which starts at the second maximal knee flexion (Gourgoulis et al., 2009). During the second pull, the barbell is rapidly accelerated through forceful and simultaneous hip extension, knee extension, and ankle plantar flexion, resembling a jumping motion (Bartonietz, 1996; Enoka, 1979, 1988; Garhammer, 1978). This extension forces the barbell to move anteriorly away from the athlete, however, in elite caliber weightlifters this anterior displacement is small (Ikeda et al., 2012). The phase is completed when the barbell reaches its peak vertical velocity (Baumann et al., 1988; Garhammer, 1978, 1991; Stone et al., 2006a).

After completing the second pull, the athlete starts to descend into a squat while the barbell still gains height (Garhammer, 1980). During this phase, known as the turnover, the athlete pulls under the barbell by using the arms to accelerate the body towards the ground (Burdett, 1982). Up until this point, the athlete's arms have remained straight and relaxed, while the legs have been used to lift the barbell (Garhammer, 1978). The barbell moves posteriorly back towards the athlete during this phase that is completed when the barbell reaches its peak height (Gourgoulis et al., 2009).

The catch phase follows the turnover, and is initiated at peak barbell height. During this phase, the athlete stabilizes the barbell overhead or on the shoulders in the bottom position of the squat under the barbell (Bartonietz, 1996; Black et al., 1991; Gourgoulis et al., 2002; Gourgoulis et al., 2009; Medvedev, 1988). The completion of this phase may be identified as the lowest vertical barbell position during the squat under the barbell.

To complete the lift, the athlete rise with the barbell in the recovery phase, which is initiated at the minimal barbell height during the squat under the barbell, and completed when the

athlete stands erect with the barbell overhead or on the shoulders in the snatch and clean, respectively (Derwin, 1990; Medvedev, 1988; Stone et al., 2006a).

## **2.2 Work Performed on the Barbell**

In order to lift the barbell, the athlete performs work against gravity (Garhammer, 1980, 1982, 1993). The work performed on the barbell causes a proportional change in its gravitational potential ( $\Delta E_p$ ) and kinetic ( $\Delta E_k$ ) energies, of which the change in gravitational potential energy is the greatest (Garhammer, 1979b, 1980, 1982, 1993). For example, Garhammer (1982) found the gravitational potential energy to increase between 1000 J and 1260 J during the pull of the snatch and clean, whereas the corresponding change in kinetic energy was between 160 J and 340 J. The changes in gravitational potential and kinetic energies can be described mathematically as presented in equation 2.1 and 2.2, where  $m$ ,  $g$ ,  $h$  and  $v$  are mass, acceleration of gravity, height, and velocity, respectively.

$$\text{[Equation 2.1]} \Delta E_p = mg\Delta h$$

$$\text{[Equation 2.2]} \Delta E_k = \frac{1}{2}m\Delta v^2$$

Since the barbell's mass and acceleration of gravity remains constant during a lift, the changes in gravitational potential and kinetic energies will be dependent on the barbell's changes in height and velocity. Mathematically, the changes in gravitational potential and kinetic energies can be related to the work performed as shown in equation 2.3.

$$\text{[Equation 2.3]} W = (mg\Delta h) + \left(\frac{1}{2}m\Delta v^2\right)$$

As work performed on the barbell relates the barbell's mass and its changes in height and velocity, it may be a valuable outcome measure when comparing weightlifting movements performed with different effort.

In addition to vertical work, the athlete performs horizontal work on the barbell during the pull. The horizontal work performed on the barbell is given by the horizontal component of the force acting on the barbell and its resultant horizontal displacement (Garhammer, 1993). The horizontal displacement of the barbell during the pull has been reported to range between 0.03 and 0.09 m towards the athlete during the first pull, 0.02 and 0.18 m away from the

athlete during the second pull, and 0.03 and 0.09 m back towards the lifter during the turnover and catch (Akkus, 2012; Garhammer, 1985; Gourgoulis, Aggelousis, Mavromatis, & Garas, 2000; Gourgoulis et al., 2002; Gourgoulis et al., 2009; Harbili, 2012; Harbili & Alptekin, 2014). However, in technically proficient weightlifters, the horizontal work performed on the barbell is a miniscule contributor to the total work performed during the pull (Garhammer, 1985, 1993; Hadi et al., 2012).

### **2.2.1 Work Performed During the First Pull**

The work performed on the barbell during the first pull is 28-55% greater than that performed during the second pull in elite male weightlifters (Gourgoulis et al., 2000; Gourgoulis et al., 2002; Gourgoulis et al., 2009; Gourgoulis, Aggeloussis, Kalivas, Antoniou, & Mavromatis, 2004; Harbili, 2012). Further, elite female weightlifters has been found to perform a work on the barbell that is 8-24% greater during the first pull than the second pull (Akkus, 2012; Harbili, 2012). As work is proportional to applied force ( $F$ ) and the resultant displacement ( $d$ ) (Equation 2.4), it is not surprising that Enoka (1979) observed that the vertical ground reaction force (GRF) impulse was greater during the first pull than the second pull. However, the magnitude of the peak vertical GRF are larger during the second pull than the first pull (Enoka, 1979; Kauhanen et al., 1984). A potential explanation of this is that the external moment arms shorten at the hip and lengthen at the knee during the transition, creating a favourable position in which large vertical force may be applied during the second pull (Enoka, 1979).

$$\text{[Equation 2.4]} W = F \cdot d$$

Since the barbell mass remains unchanged during a lift, the greater work performed on the barbell during the first pull compared with the second pull, must cause a greater change in the barbell's height, velocity, or both during this phase. Indeed, a greater change in both barbell height and velocity has been observed during the first pull compared to the second pull (Akkus, 2012; Gourgoulis et al., 2000; Gourgoulis et al., 2002; Gourgoulis et al., 2009; Gourgoulis et al., 2004; Harbili, 2012; Harbili & Alptekin, 2014).

Within subjects, the change in barbell height, and thus gravitational potential energy, should not vary to a great extent during the first pull, regardless of the effort the barbell is lifted with. In support of this notion, previous investigations have found that the change in barbell height

during the first pull does not vary within subjects (Gourgoulis et al., 2009; Harbili & Alptekin, 2014). Further, no differences has been observed in the hip extension, knee extension, or ankle plantar flexion angles during the first pull in lifts performed by the same subjects (Gourgoulis et al., 2009; Häkkinen et al., 1984; Harbili & Alptekin, 2014). Since both barbell mass and the acceleration of gravity are constant during a lift (Grieve, 1970), the change in the barbell's gravitational potential energy during the first pull will be determined by its change in height from lift-off till the knees reach their first maximal extension angle.

Since variations in the vertical barbell displacement during the first pull are small, any changes in the work performed during the first pull would alter the barbell's change in kinetic energy, as illustrated in equation 2.5. This equation can be rearranged to show that change in velocity depends on force applied ( $F$ ), displacement ( $d$ ) and mass ( $a$ ) as shown in equation 2.5a.

$$\text{[Equation 2.5]} F \cdot d = \frac{1}{2} m \cdot \Delta v^2$$

$$\text{[Equation 2.5a]} \Delta v = \left(\frac{2F \cdot d}{m}\right)^{0.5}$$

Assuming that displacement and barbell mass are constant, a change in the force applied to the barbell during the first pull would result in an altered change in barbell velocity. This is exemplified by Häkkinen et al. (1984) who reported that barbell-lifter system normalized GRF and barbell velocity simultaneously decreased with increasing barbell loads. The participants' knee extension angles at both lift-off and the first peak knee extension remained constant as barbell load was increased (Häkkinen et al., 1984). Therefore, it may be inferred that vertical barbell displacement during the first pull was unaffected by increases in barbell load. Thus, the larger force applied relative to the barbell-lifter load must have caused a greater change in barbell velocity during the first pull when lighter relative loads were used.

It seems reasonable to believe that the change in the barbell's kinetic energy during the first pull may vary when the barbell is lifted with different effort. In contrast, it does not seem like any meaningful variation in the change in gravitational potential energy may be expected during this phase. As the change in kinetic energy constitutes a small portion of the total energy change during the pull (Garhammer, 1982), it may be expected that any differences in work performed on the barbell during the first pull would be small.

### **2.2.2 Work Performed During the Transition Phase**

Barbell velocity has been found to plateau or decrease during the transition phase (Baumann et al., 1988; Enoka, 1979; Kipp & Harris, 2015). However, in elite weightlifters, drop in velocity during the transition phase is small or non-existent (Baumann et al., 1988). Despite this period of negative acceleration of the barbell, it continues to rise vertically throughout the transition phase (Enoka, 1979; Kipp & Harris, 2015). Thus, the barbell loses or maintains its kinetic energy, while its gravitational potential energy increases (Garhammer, 1982). As the barbell's height only increases by approximately 35% of its increase during the first pull and 75% of its increase during the second pull (Gourgoulis et al., 2009), the barbell's change in gravitational potential energy during this phase should be smaller than in any other phase of the pull. Further, the transition phase is the only phase of the pull where the kinetic energy decreases or plateaus (Garhammer, 1982). Therefore, it logically follows that work performed on the barbell should be smaller during the transition phase compared with the first and second pull.

The initiation of the transition phase is marked by the first maximal knee extension, which would not be expected to vary between lifts performed with different effort (Gourgoulis et al., 2009; Häkkinen et al., 1984; Harbili & Alptekin, 2014). In contrast, the shift from the transition phase to the second pull, which is marked by the second maximal knee flexion angle, has been reported to vary between individuals (Kipp et al., 2012b). Moreover, the amount of hip extension occurring during this phase may vary independent of the knee flexion angle, as the knees are flexing while the hips simultaneously are extending. If the athlete maintains the arms straight with extended elbows throughout the pull, which is considered correct lifting technique (Garhammer, 1978), the amount of knee flexion relative to hip extension during this phase will determine the magnitude of the barbell's elevation. Similarly, the velocity of the barbell will be dependent on the angular velocity of the knee relative to the angular velocity of the hip.

The knowledge base on how kinematics and kinetics of both the barbell and athlete may vary within athletes and between different athletes during the transition phase is limited. Therefore, it is hard to predict the effects of altering the effort the barbell is lifted with on the kinematics and kinetics during this phase. Moreover, the transition phase has been purported to be the most technically complex phase of the lift (Enoka, 1988). Therefore, lifting the barbell with

different effort may have unexpected consequences for the movement pattern during this phase.

### **2.2.3 Work Performed During the Second Pull**

The work performed on the barbell during the second pull is lesser in magnitude than that of the first pull (Akkus, 2012; Gourgoulis et al., 2000; Gourgoulis et al., 2002; Gourgoulis et al., 2009; Gourgoulis et al., 2004; Hadi et al., 2012; Harbili, 2012; Harbili & Alptekin, 2014). This is primarily due a smaller vertical displacement of the barbell, resulting in a small change in its gravitational potential energy (Akkus, 2012; Gourgoulis et al., 2000; Gourgoulis et al., 2002; Gourgoulis et al., 2009; Gourgoulis et al., 2004; Harbili, 2012; Harbili & Alptekin, 2014). In contrast, one study found that female weightlifters performed a work on the barbell of greater magnitude in the second pull compared to first pull (Gourgoulis et al., 2002). In comparison to the male participants in this study, the female weightlifters were more extended at the hip and more plantar flexed at the ankle at the end of the second pull (Gourgoulis et al., 2002). There were no differences in knee extension at the end of the second pull between males and females (Gourgoulis et al., 2002). Thus, it is reasonable to believe that barbell height relative to the athlete's stature at the end of the second pull was greater for female than male athletes, indicating that the displacement during second pull might vary between subjects.

Within-subject variation in vertical barbell displacement at the end of the second pull has been found to be small or non-existent (Gourgoulis et al., 2009; Harbili & Alptekin, 2014). However, the end of the second pull is marked by the instant that the barbell reaches its maximal vertical velocity (Baumann et al., 1988; Garhammer, 1978, 1991; Stone et al., 2006a). Therefore, the change in gravitational potential energy during the second pull will be dependent on the height of the barbell when it reaches its maximal vertical velocity. Thus, one can hypothesize that the change in the barbell's gravitational potential energy during the second pull can vary to some extent. Häkkinen and Kauhanen (1986) found that both elite level and district level weightlifters extended their knees to a greater extent during the power snatch and power clean compared to the snatch and clean, respectively. Although this comparison was not done on a standardized load (Häkkinen & Kauhanen, 1986), it may indicate that greater knee extension occurs when the effort in lifting the barbell is increased. A greater knee extension during the second pull would also be expected to cause a greater change in the barbell's height during this phase. However, as only knee joint angles were

reported in this study, it is not known whether ankle or hip angles differed between conditions. Further, when the shift from the transition phase to the second pull occurs may also be varied (Kipp et al., 2012b). It seems reasonable to believe that an earlier initiation of the second pull also would cause a greater change in barbell height, and thus, gravitational potential energy during this phase. However, whether the timing of second peak knee flexion angle changes with the effort the barbell is lifted with, remains to be elucidated.

The change in the barbell's velocity during the second pull has been seen to vary within subjects (Häkkinen et al., 1984; Harbili & Alptekin, 2014). Moreover, Häkkinen et al. (1984) found that barbell-lifter system normalized GRF varied within subjects during the second pull, lending it as a plausible explanation of within subject variation in barbell velocity. Therefore, it might be expected that the change in the barbell's kinetic energy can vary when the effort the barbell is lifted with is varied.

### **2.3 Barbell Mass Relative to Work Performed**

The goal in competitive weightlifting is to lift the greatest mass (Kipp et al., 2012b). In order to do so, the athlete must perform an as large as possible work on the barbell. However, it would also be favourable to use a technique that allows the largest possible barbell mass to be lifted relative to the work performed on it. By rearranging equation 2.3, it can be shown that the mass lifted relative to the work performed on the barbell, is inversely proportional to its change in height and velocity (Equation 2.6)

$$[\text{Equation 2.6}] m = \frac{W}{(g\Delta h + \frac{1}{2}\Delta v^2)}$$

Therefore, it seems that the barbell's change in height and velocity should be limited to what is strictly necessary for the successful completion of the lift in order to maximize the mass lifted relative to the work performed on the barbell (Hadi et al., 2012; Kipp & Harris, 2015). In support of this notion, more skilled weightlifters lift the barbell to a lesser peak height relative to their stature, and with a smaller peak velocity compared to their less skilled counterparts (Baumann et al., 1988; Burdett, 1982; Garhammer, 1993; Häkkinen et al., 1984; Ikeda et al., 2012).

To allow the peak barbell height and velocity to be minimized, other aspects of the lifts may have to be perfected. For example, a fast squat under the barbell during the turnover and catch



is believed to allow the barbell to be lifted to a lesser peak height, and is considered paramount to weightlifting success (Burdett, 1982; Häkkinen et al., 1984; Kauhanen et al., 1984). In order to train these aspects, it may be hypothesized that it is more favourable to lift the barbell to the minimum height required, rather than to exert maximal effort during the pull, when lifts are performed with submaximal loads. In contrast, it could be hypothesized that exerting maximal effort during the pull requires a maximal or near maximal work to be performed on the barbell regardless of barbell load. This would have two conflicting implications. First, it might be suggested that if a maximal work were performed regardless of the mass lifted, the athlete would not train at a submaximal intensity. However, the majority of the lifts prescribed in weightlifting training programs are intended to be performed at a submaximal intensity (Stone et al., 2006b). In contrast, intensity should only vary as a function of the barbell load in the minimal height variations. On the other hand, performing resistance-training exercises with the intent to execute the motion as fast or explosively as possible have been purported to positively affect neuromuscular adaptations to the resistance training (Behm & Sale, 1993). However, if the specific mechanics of these variations differ, they may also cause different adaptations in inter-muscular coordination and muscular fitness. Since no previous study has compared the biomechanics of weightlifting exercises performed with different effort, such an investigation is warranted.

## **2.4 Work Performed About the Lower Extremity Joints**

The hip extensors, knee extensors, and ankle plantar flexors are responsible for the majority of the work performed during the weightlifting pull (Garhammer, 1978, 1982). The relation between work performed on the body and barbell by these muscle groups is described in equation 2.7.

$$[\text{Equation 2.7}] W_{\text{Barbell}} + W_{\text{body}} \approx W_{\text{Ankle}} + W_{\text{Knee}} + W_{\text{Hip}}$$

To the author's knowledge, no previous study has investigated the work performed about the lower extremity joints during weightlifting exercises. However, net joint moment (NJM) and net joint power time-curves have previously been presented (Baumann et al., 1988; Enoka, 1988; Garhammer, 1978; K. Kipp, J. Redden, M. Sabick, & C. Harris, 2012a; Kipp et al., 2012b). Therefore, the general trend for work performed about the hip, knee, and ankle during the snatch and clean pull may be inferred.

The hip NJM is monophasic for the snatch and clean, with extensor moments displayed throughout the entire pull (Baumann et al., 1988; Enoka, 1988; Garhammer, 1978). Therefore, a net hip extensor work must be performed throughout the entire pull. As the net hip joint power is larger than the net hip joint power of the knee and ankle joint during the first pull (Enoka, 1988), the integrate of the hip net joint power with respect to time (i.e. net joint work) would be expected to be larger compared to that of the knee and ankle. This is not unexpected given the large forward trunk inclination during the first pull, causing the hip NJM to be as much as six times larger than the knee or ankle NJM (Enoka, 1988; Garhammer, 1978; Kipp et al., 2012b). During the transition phase, the net hip joint power decreases rapidly, despite a continuing rise in hip extension velocity (Enoka, 1988). The decrease in net hip joint power is explained by a sharp decrease of the hip extensor NJM as the moment arms of the barbell weight and gravitational force acting on the body center of mass relative to the hip shortens drastically when the trunk is repositioned to a more vertical position (Enoka, 1979, 1988; Garhammer, 1978). It would therefore be expected that the net hip extensor work performed is smaller during the transition phase compared to the first pull. During the second pull, the net hip joint power increases sharply due to a fast increase in the hip extension velocity (Enoka, 1988). However, because of the short duration of this phase compared to the first pull (Campos, Poletaev, Cuesta, Pablos, & Carratalá, 2006; Hadi et al., 2012; Harbili, 2012), the net hip extensor work during this phase would be expected to be smaller than that of the first pull.

The knee NJM time-curves are more complex, with two phases of knee extensor NJM and one phase with knee flexor NJM (Baumann et al., 1988; Enoka, 1988; Garhammer, 1978). During the majority of the first pull a knee extensor NJM is displayed. Due to relatively large positive net knee joint powers during the majority of the first pull, it is expected that a relatively large net knee extensor work is performed during this phase, although small in comparison to the net ankle plantar flexor and hip extensor work (Enoka, 1988; Garhammer, 1978). Towards the end of the first pull, the knee extensor NJM shifts to a knee flexor NJM (Baumann et al., 1988; Enoka, 1988; Garhammer, 1978). Simultaneously, the net knee joint power turns negative, indicating that a small amount of eccentric net knee flexor work is performed at the end of the first pull (Enoka, 1988). During the transition, a knee flexor moment in conjunction with a small positive net knee joint power would result in a concentric net knee flexor work being performed, pulling the knee into flexion (Baumann et al., 1988; Enoka, 1988; Garhammer, 1978). Like during the first pull, both the knee NJM and net knee

joint power shifts directions toward the end of the phase, which would result in a small eccentric net knee extensor work being performed prior to the initiation of the second pull. During the second pull, the net knee joint power increases rapidly due to a sharp increase in both knee extension velocity and knee extensor NJM (Enoka, 1988; Garhammer, 1978). Therefore, it would be expected that a relatively large net knee extensor work be performed during the second pull.

Like the hip NJM, the ankle NJM is also monophasic, with ankle plantar flexor NJM displayed throughout the entire pull (Baumann et al., 1988; Enoka, 1988). The net ankle joint powers are smaller during the first pull compared to the second pull (Enoka, 1988). However, due to the longer duration of the first pull compared to the second pull, it may be expected that the net ankle plantar flexor work performed is similar in the first and second pull (Campos et al., 2006; Hadi et al., 2012; Harbili, 2012). During the transition phase, the net ankle joint power shifts from positive to negative, whereas the ankle NJM remains one of plantar flexion (Baumann et al., 1988; Enoka, 1988). Thus, it would be expected that an eccentric net ankle plantar flexor work would be performed during this phase.

#### **2.4.1 Load distribution**

As discussed above, it appears that the work performed on the barbell during the pull might differ in lifts performed with different effort. Due to the relation between the work performed on the barbell and the work performed about the lower extremity joints (Equation 2.6), an increase in the work performed on the barbell would be expected to require a larger work to be performed about the lower extremity joints. However, previous research on other movement tasks have found that joint mechanical efforts do not scale linearly with increases in the work performed (Flanagan & Salem, 2008; McNitt-Gray, 1993). For example, Flanagan and Salem (2008) found that the percentage contribution of the net knee extensor work to the total work performed decreased significantly with increasing load. In contrast, the percentage contribution of the net hip extensor work to total work increased significantly with increasing load, while percentage net ankle plantar flexor work contribution remained unchanged (Flanagan & Salem, 2008). In addition it was seen that the relative contribution of the hip extensor and ankle plantar flexor NJM to the average support moment increased with increasing loads from 25 – 75% of three repetitions maximum (Flanagan & Salem, 2008). The knee extensor NJM contribution to average support moment reflected the net knee extensor work contribution to total work (Flanagan & Salem, 2008). Another study quantified the

relative muscular effort (RME) of the lower extremity joints during the squat exercise have reported similar results (Bryanton, Kennedy, Carey, & Chiu, 2012). Specifically, Bryanton et al. (2012) found that the RME of the ankle and hip increase with increasing load. In contrast, the RME at the knee joint remained unaffected when loads were increased beyond 50% of one repetition maximum (1 RM) in a deep squat (Bryanton et al., 2012). In other words, the hip extensor and ankle plantar flexor RME increased disproportionately more than the knee extensor RME as the barbell load increase in a deep squat (Bryanton et al., 2012).

Work is the product of force and displacement (Equation 2.4). Further, the vertical barbell displacement in weightlifting has been seen to largely vary as a function of the athlete's stature (Baumann et al., 1988; Burdett, 1982; Garhammer, 1993; Gourgoulis et al., 2000; Häkkinen et al., 1984; Stone et al., 2006a). Thus, one would expect that force must increase if more work is to be done in lifts performed with greater effort. Flanagan and Salem (2008) hypothesized that an increase in vertical GRF would act on the foot segment, increasing the ankle plantar flexor NJM. During the clean, Kipp, Harris, and Sabick (2011) observed that ankle plantar flexor NJM increased with increasing barbell load. Assuming that an increase in the effort the barbell is lifted with would result in an increase in vertical GRF, one would expect that the ankle plantar flexor NJM also would be greater in a lift performed with greater effort, without an increase in barbell load. Further, the ankle plantar flexor NJM also acts on leg segment, which has been hypothesized to reduce the knee extensor demand (Flanagan & Salem, 2008). In support of this notion, Kipp et al. (2011) found that knee extensor NJM did not increase with increasing load in the pull of the clean. Lastly, Flanagan and Salem (2008) suggested that if knee extensor NJM does not increase proportionately to ankle plantar flexor NJM, the large GRF acting on the thigh segment will increase the hip extensor demand, which has also been observed during the clean (Kipp et al., 2011). Another potential mechanisms of such a shift in load distribution is changes in the centre of pressure (Flanagan & Salem, 2008), which would change the length of the moment arm of the GRF acting on the foot.

Nonetheless, it seems reasonable to assume that an increase in effort during the pull will result in a disproportionate increase in the joint mechanical efforts that is similar to those reported for the squat exercise (Bryanton et al., 2012; Flanagan & Salem, 2008). Further, large shifts in joint mechanical efforts could potentially have an effect on both the inter-muscular coordination of the muscles involved, and how these adapt to weightlifting training (Bryanton

et al., 2012; Takano, 1987a). However, since no studies have compared the work performed on the barbell, or the work performed about the lower extremity joints during snatches or cleans performed with different effort, these questions are still to be elucidated.

### **3. Theoretical Basis for the Methods**

#### **3.1 Study Design**

Comparisons of different motor tasks or variations of the same motor task are common in biomechanics research (e.g. Chiu & Moolyk, 2015; Chiu & Salem, 2006; Garhammer & Gregor, 1992; Häkkinen & Kauhanen, 1986; Moolyk, Carey, & Chiu, 2013). The study design most commonly utilized to make such comparisons is the cross-sectional study design. In this design, measurements are taken at a single point in time, from a sample recruited from a specific population (Mann, 2003). The time and cost efficiency of the cross-sectional design gives it distinct benefits over many other study designs, such as experimental designs (Mann, 2003). Cross-sectional studies are therefore useful for identifying relationships that may be worth investigated further using experimental designs (Mann, 2003). However, due to its simplicity, the cross-sectional study design also has certain limitations.

The most important limitation associated with the cross-sectional study design, is that it does not allow for a causal relationship between the dependent and independent variables to be established (Mann, 2003; Trochim & Donnelly, 2007). Therefore, this design should not be used to investigate causal relationships. Another limitation to the cross-sectional study design is that it only represents the sample at one time point (Trochim & Donnelly, 2007). However, biomechanical variables of interest in weightlifting research have been consistent among skilled weightlifters over several decades of competition (e.g. Burdett, 1982; Garhammer, 1979a, 1985; Gourgoulis et al., 2000; Gourgoulis et al., 2009; Gourgoulis et al., 2004; Musser, Garhammer, Rozenek, Crussemeyer, & Vargas, 2014). Therefore, the time aspect does not seem to pose an immediate threat to the external validity of cross-sectional studies investigating weightlifting tasks.

#### **3.2 Sampling**

A number of different sampling strategies may be used to recruit participants for a research study. The strategy considered least prone to introduce selection bias and error is random sampling (Kothari, 2004). However, in many biomechanical studies, a sample must be drawn from a population with experience performing a specific task, such as the clean in weightlifting. Further, in studies attempting to identify optimal movement patterns, the participants may be required to be experts performing the specific task. Since the equipment used for many biomechanical analyses cannot be easily moved between different locations,

the geographical unit from which the sample must be drawn is often relatively small. Thus, in order to obtain a sufficiently large sample from a limited population, random sampling may not be feasible. In such situations, a more practical sampling approach may be purposive sampling as described by Trochim and Donnelly (2007). In this sampling approach, the researchers purposely select participants belonging to a narrowly defined group of experts on the basis that this sample will represent the population as a whole (Kothari, 2004; Trochim & Donnelly, 2007). However, since expert sampling is a non-random sampling strategy, the probability of the sample actually being representative of this population cannot be estimated (Kothari, 2004; Trochim & Donnelly, 2007). This poses a limitation to the external validity of this sampling strategy. The external validity may, however, be improved by replicating the findings in subsequent studies using different sets of the population.

### **3.3 Motion Analysis**

Two- and three-dimensional (2-D and 3-D, respectively) motion analyses are among the most commonly used methods in biomechanics research. The theoretical basis of these methods is derived from classical mechanics (Cappozzo, 1984; Cappozzo, Della Croce, Leardini, & Chiari, 2005). Specifically, the body is assumed to consist of a link of segments, where each segment is treated as a rigid body (Cappozzo et al., 2005; Kadaba, Ramakrishnan, & Wootten, 1990). The kinematics of each segment in the rigid-link model is calculated from either 2-D or 3-D displacement data. The calculated kinematics are then combined with knowledge of the segments' inertial properties as well as measured forces to calculate the kinetics of the motion (Davis, Ounpuu, Tyburski, & Gage, 1991). As the kinematics of the motion greatly influences the kinetics calculated (Winter, 2009; Winter, Sidwall, & Hobson, 1974), the theoretical foundation of different methods used to calculate both the kinematics and kinetics of a motor task is discussed in this chapter.

#### **3.3.1 Instruments**

Different instruments may be used to collect displacement and force data. Digital video is most commonly used to collect 2-D displacement data (e.g. Garhammer & Newton, 2013; Hoover, Carlson, Christensen, & Zebas, 2006). However, linear position transducers and accelerometers have also been used to measure displacement, particularly of external objects, such as a barbell (e.g. Cormie, McCaulley, Triplett, & McBride, 2007; Garhammer & Newton, 2013; Hardee et al., 2013; Koshida, Urabe, Miyashita, Iwai, & Kagimori, 2008). Although only digital video and accelerometers may be used to determine segment

displacement, all are considered valid methods for obtaining the kinematics of external objects of interest (Cormie, McBride, & McCaulley, 2007; Garhammer & Newton, 2013; Koshida et al., 2008; Morris, 1973). However, digital video has several advantages over accelerometers and linear position transducers (Dæhlin et al. Appendix A). First, no force is exerted on the object when using digital video alone. Moreover, instrumentation used to facilitate digitization of the points of interest generally exerts a smaller force on the object than accelerometers and linear position transducers (Dæhlin et al. Appendix A). Second, the video record may be used to identify movement occurring in other planes than the one investigated, which may invalidate planar assumptions in 2-D analysis (Garhammer, 1998). Third, consumer cameras and open source software may be used for 2-D video analysis, which are highly accessible at a low cost (Dæhlin et al. Appendix A). Although, motion of external objects may occur almost exclusively in two planes, such as is the case with the barbell during a clean (Garhammer, 1998), most human motion occurs in three planes and segment displacements in all three planes should therefore be evaluated (Chao, 1980; Grood & Suntay, 1983).

Today, optoelectronic video systems are most commonly used to obtain 3-D displacement data (Chiari, Della Croce, Leardini, & Cappozzo, 2005; Della Croce, Cappozzo, & Kerrigan, 1999). These systems use a minimum of two charge-coupled device cameras to locate points identified by reflective or light emitting markers in 3-D space (Chiari et al., 2005). The widespread use of these systems may be attributed to their distinct advantages over other motion capturing techniques, such as digital video recordings and goniometers (Chiari et al., 2005). One of the advantages of optoelectronic systems is that the location of markers are automatically identified using specialized software (Chiari et al., 2005). This drastically reduces processing time compared to digital video recordings where points of interest are manually digitized (Garhammer & Newton, 2013). A second advantage is that the location and orientation of each segment in the rigid-link may be identified both in space and in relation to each other (Cappozzo et al., 2005). In contrast, goniometers may only be used to identify a segment's orientation relative to another segment (Cappozzo, 1984; Chao, 1980). Lastly, these systems can detect markers in 3-D space with high accuracy (Chiari et al., 2005). Despite being considered the "gold standard" for motion analysis purposes, these systems also have inherent limitations that introduces measurement error (Chiari et al., 2005). Among the sources of error are optical distortions, electronic noise, marker flickering and marker merging (Chiari et al., 2005). Although all error from optical distortion cannot be addressed,



proper calibration reduces error substantiating from this phenomenon (Chiari et al., 2005). Error introduced by electronic noise and marker flickering or merging may be addressed with proper filtering (see section 3.3.3), and marker (see section 3.3.2) and camera placement, respectively.

In addition to collecting displacement data, forces acting on the body must be measured or estimated. The external forces acting on the body are gravitational forces, GRFs and/or other external forces, such as forces exerted on one player by other players in American football (Cappozzo, 1984; Winter, 2009). In most biomechanical research, gravitational forces acting on each segment are estimated from anthropometrics data, whereas GRFs in three dimensions are directly measured using specialized dynamometers known as force platforms (Cappozzo, 1984; Davis et al., 1991; Winter, 2009).

### **3.3.2 Marker Configurations**

When 2-D video is used, it is not required that markers are attached to each segment. However, many software programs include an auto-tracking feature that uses pattern recognition to track the trajectory of a point of interest (Garhammer & Newton, 2013). For a point of interest to be successfully identified using pattern recognition, it must be distinctive, creating a strong contrast to the surrounding image (Garhammer & Newton, 2013). To aid in creating a distinctive pattern from the surrounding image, it has been suggested that reflective markers or coloured tape may be used (Garhammer & Newton, 2013). However, these techniques may not always be effective. In contrast, Dæhlin et al. (Appendix A) found that the barbell end could be successfully auto-tracked when instrumented with a marker using light emitting diodes. It was therefore suggested that this technique might be employed to facilitate auto-tracking of barbell displacement (Dæhlin et al. Appendix A).

In contrast to when using digital video, 3-D displacement data obtained using optoelectronic systems require either reflective or light emitting markers to be attached to the points to be tracked (Chiari et al., 2005). Due to the inconvenience of the wiring required by the light emitting markers, reflective markers are most commonly used (Chiari et al., 2005). A minimum of three markers must be attached to each segment in order to describe its position and orientation in 3-D space (Cappozzo, Cappello, Croce, & Pensalfini, 1997; Cappozzo et al., 2005; Woltring, 1991).

The markers attached to each segment may be categorized as bone-mounted markers, skin mounted markers, or markers mounted on rigid plates (Cappozzo, Catani, Della Croce, & Leardini, 1995; Fuller, Liu, Murphy, & Mann, 1997; Reinschmidt et al., 1997). As skin and soft tissue move relative to the underlying bone, markers anchored directly in the bones are considered most accurate (Fuller et al., 1997; Manal, McClay, Stanhope, Richards, & Galinat, 2000). The relative motion between skin mounted markers and bone mounted markers have been reported to be as large as 20 mm (Fuller et al., 1997; Reinschmidt et al., 1997). However, due to the invasive nature of bone pin markers, non-invasive techniques are most commonly used (Reinschmidt et al., 1997). Comparisons of different non-invasive marker configurations have revealed that markers attached to rigid plates provide more accurate results than markers mounted directly on the skin (Manal et al., 2000). However, since these markers do not provide an anatomical description of the segment, their location must be related to an anatomically defined coordinate system (see section 3.4.4). In order to do so, a static calibration trial must be completed, in which the participant is recorded wearing the tracking markers, as well as additional calibration markers placed on bony landmarks (Cappozzo et al., 2005; Della Croce et al., 1999). Although standardized locations for calibration markers have been suggested (Davis et al., 1991; Kadaba et al., 1990), many different anatomical landmarks may be used for this purpose (C-motion, 2016).

### **3.3.3 Noise Removal**

Displacement and force data are both subject to random (noise) and systematic error (bias). Unlike bias that typically skew the signal, noise may be assumed to be independent of the measured signal (Wood, 1982). Although the effect of noise on displacement data may be small, these errors magnify when displacement data is differentiated to yield velocities and accelerations (Pezzack, Norman, & Winter, 1977; Winter et al., 1974). As differentiation is necessary in the calculation kinetic variables (Wells & Winter, 1980; Winter et al., 1974), noise must be removed from the raw marker and GRF signal before calculation of further variables can commence.

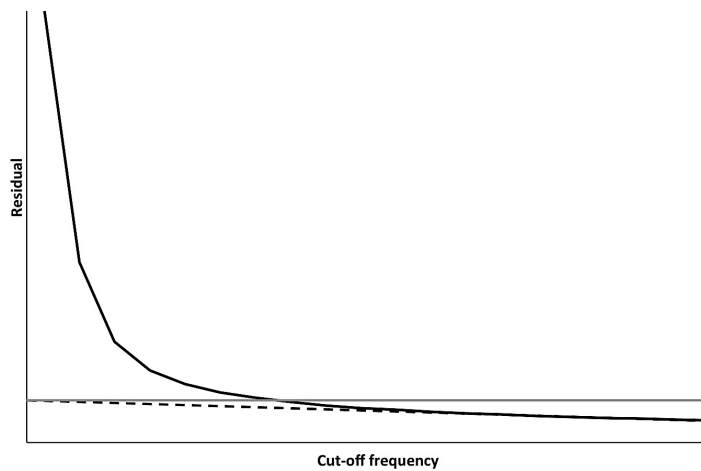
Many different techniques may be used to remove noise from the signal (Winter et al., 1974; Woltring, 1986; Wood, 1982). However, splines and digital filters appear to be the most commonly recommended techniques (Pezzack et al., 1977; Winter et al., 1974; Woltring, 1986; Wood, 1982). A digital filter is a mathematical function that uses equispaced numbers as input, and outputs a number set of a limited frequency determined by its cut-off (Wood,

1982). In contrast, splines consist of a number of low-order polynomials that are pieced together to provide a continuous function (Wood, 1982).

For a digital filter to remove as much noise as possible while retaining the signal, an appropriate cut-off frequency must be selected. To aid the researcher in the selection of an appropriate cut-off, a residual analysis may be used (Wells & Winter, 1980; Wood, 1982). For this purpose, residuals ( $R$ ) are computed over a spectre of cut-off frequencies ( $fc$ ) as shown in equation 3.2, where  $x_i$  and  $\hat{x}_i$  are the raw and filtered values of the  $i^{th}$  sample, respectively (Winter, 2009).

$$\text{[Equation 3.2]} R(fc) = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \hat{x}_i)^2}$$

The computed residuals are then plotted against cut-off frequencies as illustrated in figure 3.1.



**Figure 3.1:** A graph of residuals (thick black line) plotted against different cut-off frequencies. The dashed line indicates the noise removed at different cut-off frequencies, while the thin gray line indicates the level of noise present in the data. The residuals rising above the gray line represents signal distortion.

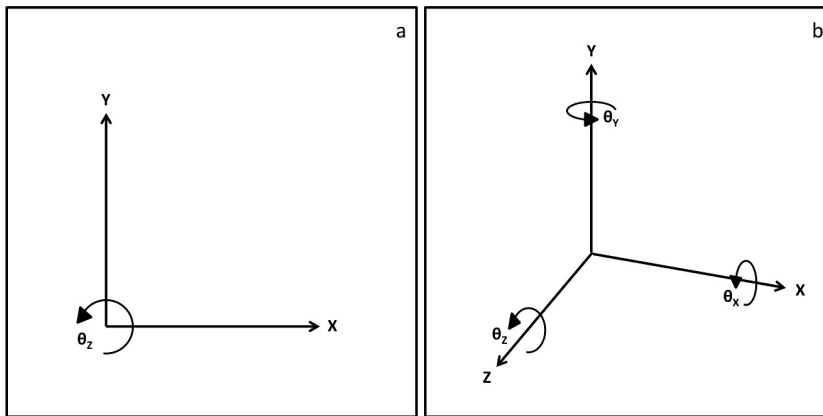
If the signal was comprised entirely of noise, the amount of noise removed should increase linearly with decreasing cut-off frequencies, as illustrated by the dashed line in figure 3.1 (Wells & Winter, 1980). Thus, the noise present in the data may be estimated from this extrapolated line as indicated by the thin gray line in figure 3.1 (Wells & Winter, 1980). The residuals that rise above the noise represents signal distortion (Wells & Winter, 1980). The

cut-off frequency at which to filter data should be selected so that the filter removes as much noise as possible while limiting signal distortion (Winter, 2009; Wood, 1982).

A residual analysis may reveal that different cut-off frequencies are optimal for noise removal in displacement and force data. However, filtering displacement and force data at different cut-off frequencies has been found to introduce artefacts (Kristianslund, Krosshaug, & van den Bogert, 2012). Therefore, it is recommended that the same cut-off frequency be used for both displacement and force data (Bisseling & Hof, 2006; Kristianslund et al., 2012). Since the calculation of NJMs using inverse dynamics requires accurate segment accelerations (see section 3.3.6), displacement data should be used to determine an optimal cut-off (Kristianslund et al., 2012).

### **3.3.4 Coordinate Systems**

To express the location and orientation of each rigid segment in 2-D or 3-D space, the points of interest or markers must be expressed in reference to a known point. This is achieved by assigning a Cartesian coordinate system with known origin (Cappozzo et al., 2005; Winter, 2009). This coordinate system is often referred to as the laboratory coordinate system, and consists of three orthogonal axes X, Y, and Z, commonly designated the unit vectors **i**, **j**, **k** along these axes. However, in 2-D space, translation may only occur along two of these axes, whereas rotation occurs about the remaining axis (Winter, 2009). Thus, each segment has three degrees of freedom in a 2-D system, two translational (i.e. X and Y coordinate) and one rotational (i.e. rotation about Z [ $\theta_Z$ ]). In contrast, translation may occur along, and rotation may occur about all three axes in 3-D systems (Grood & Suntay, 1983). Therefore, a segment has six degrees of freedom in 3-D space, three translational (i.e. X, Y, Z coordinate) and three rotational (i.e.  $\theta_X$ ,  $\theta_Y$ ,  $\theta_Z$ ). Figure 3.2a and 3.2b depicts a 2-D and 3-D Cartesian coordinate system, respectively.



**Figure 3.2:** Illustration of a Cartesian coordinate used for two-dimensional (panel a) or three-dimensional (panel b) analysis. In panel a, the Z-axis may be imagined to be pointing straight out of the picture.

The use of a Cartesian laboratory coordinate system allows the location any point of interest to be described in terms of their two or three coordinates and coinciding unit vectors in 2-D and 3-D systems, respectively (Cappozzo et al., 1995). Although description of a segment's orientation is straightforward in 2-D systems, the orientation of a segment in 3-D space requires further coordinate systems to be assigned (see section 3.3.5).

One of these coordinate systems is arbitrarily assigned to the tracking markers, and allows each segment's motion to be defined relative to the laboratory coordinate system as time progresses (Cappozzo et al., 1995; Cappozzo et al., 2005; Kadaba et al., 1990). However, the marker coordinate systems are most often not consistent with our anatomical understanding of segment motion (Cappozzo et al., 1995). Moreover, different laboratories may use different marker configurations, or the marker configuration may be changed for analyses of different tasks (Winter, 2009). To allow the motion of each segment to be interpreted consistently with our anatomical understanding of each segment's motion, another coordinate system is assigned based on markers placed on bony landmarks during a standing calibration trial (Cappozzo et al., 1995; Cappozzo et al., 2005). The calculation of these segment coordinate systems has been described for a number of specific marker sets (Cappozzo et al., 1995; Davis et al., 1991; Kadaba et al., 1990). However, a more general approach is defined by the manufacturer of a software program used for processing of 3-D motion data (C-motion, 2015). If markers are used to define the proximal and distal ends of each segment, as well as their frontal plane, the segment coordinate systems may be computed in the following steps

(C-motion, 2015): First, the proximal and distal ends of each segment are determined by calculating the midpoint between the medial and lateral markers placed on the proximal and distal segment ends, respectively. The proximal or distal segment endpoints may be used as origins for the segment coordinate systems. Second, the vertical axes of the coordinate systems are determined as a line passing through both segment endpoints from distal to proximal end. The frontal plane is then fitted to the location of the proximal and distal segment end markers in a least squares sense. The anterior-posterior axes of the coordinate systems are then defined as perpendicular to the frontal plane, and the medio-lateral axes are defined as perpendicular to both the superior-inferior and anterior-posterior axes. The advantage of such a general description is that the same method may be applied to a vast number of marker sets (C-motion, 2015).

### 3.3.5 Segment and Joint Angles

Segment and joint angles describes the orientation of one segment with respect to the laboratory coordinate system or to another segment, respectively (Baker, 2001; Cappozzo et al., 2005; Chao, 1980; Davis et al., 1991; Della Croce et al., 1999; Kadaba et al., 1990; Wu & Cavanagh, 1995). In order to calculate the angle of a segment in 2-D, coordinates of two points along the long axis of the segment must be known (Winter, 2009). Using trigonometry, we can easily compute a segment's angle ( $\theta_s$ ) with respect to horizontal from the two individual points' horizontal ( $X_1$  and  $X_2$ ) and vertical ( $Y_1$  and  $Y_2$ ) position coordinates as show in equation 3.2 (Winter, 2009).

$$[\text{Equation 3.2}] \theta_s = \arctan \frac{Y_2 - Y_1}{X_2 - X_1}$$

Once the 2-D segment angles are known, a 2-D joint angle ( $\theta_j$ ) may be computed by subtracting the angle of the distal segment ( $\theta_{sd}$ ) from the angle of the proximal segment ( $\theta_{sp}$ ) as shown in equation 3.3 (Winter, 2009).

$$[\text{Equation 3.3}] \theta_j = \theta_{sp} - \theta_{sd}$$

In contrast to 2-D segment and joint angles, 3-D segment and joint angles requires a transformation from a designated reference coordinate system (e.g. laboratory coordinate system), to the segment coordinate system of interest to be performed. One way of performing such a transformation is using an ordered sequence of rotations about the three axes of the

coordinate system (Cappozzo et al., 2005; Chao, 1980; Cole, Nigg, Ronsky, & Yeadon, 1993; Grood & Suntay, 1983; Kadaba et al., 1990; Woltring, 1994). If we consider a vector  $\mathbf{y}$  describing a point in the reference coordinate system, and the vector  $\mathbf{x}$  describing the same point in the segment coordinate system of interest, then the relation between these vectors may be expressed mathematically as shown in equation 3.4 (Grood & Suntay, 1983; Woltring, 1991, 1994).

$$\text{[Equation 3.4]} \quad \mathbf{y} = [\mathbf{R}]\mathbf{x} + \mathbf{p}$$

In this equation,  $\mathbf{p}$  is a position vector locating the origin of the segment coordinate system of interest, and  $[\mathbf{R}]$  is an ordered matrix product of three orthogonal component matrices that each describes the rotation about an individual axis. For example, if an XYZ Cardan sequence is used, the coordinate system is first rotated by an angle  $\phi_x$  about its x-axis, yielding two newly oriented axes,  $y'$  and  $z'$ . Second, the coordinate system is rotated by an angle  $\phi_y$  about the  $y'$ -axis, yielding the newly oriented  $x''$ - and  $z''$ -axes. Lastly, the coordinate system is rotated by an angle  $\phi_z$  about the  $z''$ -axis, completing the transformation (Winter, 2009). This transformation may be expressed mathematically using three component matrices constructed from the direction of cosines matrix as shown in equation 3.5-3.8 (Woltring, 1991, 1994).

$$\text{[Equation 3.5]} \quad [\mathbf{R}] = [\mathbf{R}_x(\phi_x)][\mathbf{R}_y(\phi_y)][\mathbf{R}_z(\phi_z)]$$

$$\text{[Equation 3.6]} \quad [\mathbf{R}_x(\phi_x)] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi_x & \sin \phi_x \\ 0 & -\sin \phi_x & \cos \phi_x \end{bmatrix}$$

$$\text{[Equation 3.7]} \quad [\mathbf{R}_y(\phi_y)] = \begin{bmatrix} \cos \phi_y & 0 & \sin \phi_y \\ 0 & 1 & 0 \\ -\sin \phi_y & 0 & \cos \phi_y \end{bmatrix}$$

$$\text{[Equation 3.8]} \quad [\mathbf{R}_z(\phi_z)] = \begin{bmatrix} \cos \phi_z & \sin \phi_z & 0 \\ -\sin \phi_z & \cos \phi_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The example above used an XYZ Cardan sequence, however, a total of twelve Cardan/Euler sequences may be used to describe the orientation of one coordinate system with reference to another (Winter, 2009). Since the rotation sequence is non-commutative, the selected

sequence should provide angles that are consistent with our anatomical understanding of the motion (Baker, 2001; Woltring, 1991, 1994). For the purpose of describing segment angles, the Cardan sequence that corresponds to tilt, rotation, and obliquity was recommended by the International Society of Biomechanics (Wu & Cavanagh, 1995). However, Baker (2001) found that the Cardan sequence corresponding to rotation, obliquity, and tilt resulted in mathematically sound pelvic angles that more accurately represented pelvic motion as it is anatomically interpreted. Therefore, he recommended to use this Cardan sequence for the calculation of segment angles (Baker, 2001).

For the purpose of calculating joint angles, it appears to be general agreement that the rotation sequence corresponding to rotation about the flexion/extension axis, then abduction/adduction axis, and last endo-/exo-rotation axis should be used (Cole et al., 1993; Davis et al., 1991; Grood & Suntay, 1983; Kadaba et al., 1990; Woltring, 1994). However, the joint angles may be calculated using different methods. For example, the conventional Cardan/Euler method described above may be used (Davis et al., 1991; Kadaba et al., 1990). Another method that may be used to calculate joint angles are joint coordinate systems (Grood & Suntay, 1983). For example, the joint coordinate system of the knee may be constructed by using the medio/lateral axis of the thigh segment coordinate system about which flexion/extension occurs, and the longitudinal axis of the leg segment coordinate system about which endo-/exo-rotation occurs (Grood & Suntay, 1983). The cross product of these two axes defines a “floating” axis about which abduction/adduction occurs (Grood & Suntay, 1983). In practice however, this provides similar results as when the Cardan sequence corresponding to rotation about the flexion/extension axis, then abduction/adduction axis, and last endo-/exo rotation axis is used (Cole et al., 1993; Woltring, 1994). A third method that may be used to express relative orientation between two coordinate systems is to use the finite helical axis method (Woltring, 1991). This method defines any finite movement from a reference position as a translation along and rotation about an axis vector (Woltring, 1991). The major advantage of the Cardan/Euler and joint coordinate system methods is that these provide joint angles consistent with our anatomical interpretation of joint motion (Grood & Suntay, 1983). However, these methods are prone to a computational condition where all components cannot be uniquely defined, known as a “gimbal lock” (Chao, 1980; Woltring, 1994), which may be circumvented using helical angles (Woltring, 1991). However, a gimbal lock rarely occurs for lower extremity motion (Grood & Suntay, 1983).



### 3.3.6 Inverse dynamics

When the kinematics of the movement of interest is calculated; it may be combined with knowledge of the forces acting on the body and individual segments' inertial properties in order to determine the kinetics of the motion (Davis et al., 1991). Iterative Newton-Euler inverse dynamics is used for the purpose of calculating the joint reaction forces and NJM acting on each segment in the rigid-link model. Specifically, the Newtonian equations of motion are used to calculate the joint reaction forces, while the NJMs are computed using Euler's equations of motion (Davis et al., 1991; Winter, 2009). The only difference in calculating joint reaction forces and NJMs in 2-D and 3-D is the number of planes in which these are determined. The general equations used to compute the joint reaction force and NJM in the  $i^{th}$  plane are given in equations 3.9 and 3.10 (Davis et al., 1991; Winter, 2009).

$$\text{[Equation 3.9]} \sum \mathbf{F}_i = m\mathbf{a}_i$$

$$\text{[Equation 3.10]} \sum M_i = I_i\alpha_i + (I_k - I_j)\omega_j\omega_k$$

In the equations,  $\mathbf{F}$  is force,  $M$  is moment,  $\mathbf{a}$  is linear acceleration,  $I$  is inertia,  $\alpha$  is angular acceleration, and  $\omega$  is the angular velocity. The subscripts  $j$  and  $k$  are used to denote the 2<sup>nd</sup> and 3<sup>rd</sup> axis of the coordinate system, respectively. The second term in equation 3.10 is omitted in 2-D analyses.

Although variables calculated using inverse dynamics provide important information about the movement of interest, they are subject to several inherent limitations. First, only minimum moments acting about a joint are estimated when using inverse dynamics calculations (Schache & Baker, 2007). Thus, co-contraction by antagonistic muscles, as well as energy dissipated due to stretch, or generated by elastic recoil in tendons and ligaments, are not accounted for in this estimate (Mansour & Audu, 1986; McFaul & Lamontagne, 1998). Further, the segments in the link-model are assumed to be rigid, and energy dissipated through deformation of body segments are therefore not represented in the equations (Cappozzo et al., 2005). Moreover, contributions of individual muscles to NJM cannot be determined using this approach (Schache & Baker, 2007). These limitations does not invalidate the use of the inverse dynamics calculations, but raises the point that data calculated using inverse dynamics should be interpreted with caution (Robertson & Winter, 1980).

### 3.3.7 Work and Energy

Mechanical work is a measure of energy flow from one body to another body, and is closely related to mechanical energy, which is a measure of a body's ability to perform work (Winter, 2009). In biomechanical systems, potential and kinetic energy are usually the only energies considered. Kinetic energy may be either translational or rotational. In order to increase the energy of a body, work must be performed on it. Therefore, the mathematical relationship between work and energy in biomechanical systems may be expressed as shown in equation 3.11, where  $W$  is mechanical work, and  $\Delta E_P$ ,  $\Delta E_{TK}$ , and  $\Delta E_{RK}$  are potential, translational kinetic, and rotational kinetic energies, respectively.

$$[\text{Equation 3.11}] W = \Delta E_P + \Delta E_{TK} + \Delta E_{RK}$$

In weightlifting, the work-energy relationship has been utilized to compute the work performed on the barbell, by summing its changes in gravitational potential and kinetic energies. The numerical computations of net changes in the barbell's translational kinetic and gravitational potential energies of the barbell has been described in detail by Garhammer (1993). Specifically, the barbell's change in gravitational potential energy may be computed as the product of the barbell mass ( $m$ ), acceleration of gravity ( $g$ ) and the change in barbell height as shown in equation 3.12, where  $h_f$  and  $h_i$  is the final and initial barbell heights, respectively.

$$[\text{Equation 3.12}] \Delta E_P = mg(h_f - h_i)$$

The vertical component of the barbell's change in translational kinetic energy may be computed as the product of the barbell mass and its vertical velocity squared, divided by two, as shown in equation 3.13. In the equation,  $v_f$  and  $v_i$  are the final and initial vertical barbell velocities, respectively.

$$[\text{Equation 3.13}] \Delta E_{TK} = \frac{m(v_f^2 - v_i^2)}{2}$$

The horizontal component of the work performed may be also be computed from Newton's second law of motion, but is often ignored in weightlifting studies (Garhammer, 1993). Although this poses a limitation to the computation, horizontal work performed on the barbell has been found to contribute as little as 1% to the total work performed in skilled weightlifters

(Garhammer, 1985). Thus, ignoring the horizontal work performed on the barbell during weightlifting exercises does not appear to invalidate the work computation, although this will largely depend on the research question at hand.

Another limitation to this work computation is that the elastic energy changes caused by deformation of the barbell are not considered. Chiu, Schilling, Fry, and Salem (2008) found significant differences in barbell kinematics when quantifying differences between tracking markers placed on the barbell ends, versus a reflective tape wrapped around the barbell centre. They suggested that tracking the barbell centre would give a more accurate measure of vertical barbell displacement than when tracking barbell ends (Chiu et al., 2008). However, computations of work performed on the barbell was not largely affected by barbell deformation, and was therefore considered appropriate as long as a considerable amount of barbell tilt is not present (Chiu et al., 2008). A way of circumventing issues arising from barbell tilt and rotation is to average the position coordinates of markers placed on the barbell ends.

Rotational work is the product of inertia and angular displacement. However, in biomechanical systems rapid-time course changes in the work performed by the muscles causing joint motion occur, and therefore, joint power has commonly been computed (Winter, 2009). Joint power ( $P$ ) in the  $i^{th}$  plane is the product of the NJM acting about a joint ( $j$ ) and its angular velocity ( $\omega$ ), and can be expressed mathematically as presented in equation 3.14 (Robertson & Winter, 1980).

$$\text{[Equation 3.14]} \quad P_{ij} = NJM_{ij}\omega_{ij}$$

As the joint power is the rate at which work is performed, the joint work may be computed by integrating the joint power between time 1 ( $t_1$ ) and time 2 ( $t_2$ ) as shown in equation 3.15 (Winter, 2009).

$$\text{[Equation 3.15]} \quad W_{ij} = \int_{t_1}^{t_2} P_{ij} dt$$

However, as the NJM goes into the joint power calculation, and thus affects the joint work computed, this variable has the same inherit limitations as the NJM does.

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## 4. Research Article

### **Mechanical work performed during three variations of the clean exercise**

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## **Abstract**

The purpose of this research was to compare the work performed on the barbell and about the lower extremity joints during the pull of cleans performed with different objectives. Eight experienced weightlifters performed cleans with sufficient effort to lift the barbell to the minimum height required to receive it in a full squat (minimal height clean); or with maximum effort to elevate the barbell as high as possible and receiving it in a full (maximal effort clean) or partial (power clean) squat. Work performed on the barbell and about the lower extremity joints were computed from marker trajectories and ground reaction forces. Total barbell work, lower extremity joint work, knee extensor work, and knee flexor work were smaller in the minimal height clean than the maximal effort and power cleans ( $P < 0.05$ ). Moreover, ankle plantar flexor work was smaller in the minimal height clean than the power clean ( $P < 0.05$ ). The minimal height clean allowed the same barbell mass to be lifted by performing a smaller work on the barbell and about the lower extremity joints. The smaller joint work performed during the minimal height clean was primarily accounted for by a smaller knee flexor and extensor work.

**Keywords:** *Motion analysis, Resistance exercise, Weightlifting, Performance optimization, Technique.*

## Introduction

One event contested in weightlifting is the clean & jerk. This event is initiated with lifting the barbell from the ground to the shoulders in one continuous movement during the clean (Stone, Pierce, Sands, & Stone, 2006a). Although there are some general kinetic and kinematic characteristics for the clean, competitive weightlifters may perform this exercise with different objectives. For example, maximal effort can be exerted throughout the propulsion phase to elevate the barbell as high as possible (Bartonietz, 1996; Hedrick, 2004; Takano, 1987, 1988). Subsequently, the barbell is received on the shoulders in either a full (maximal effort clean) or partial squat (power clean). In contrast, the barbell can also be raised to the minimum height (minimal height clean) required for the athlete to successfully receive it on the shoulders in a full squat (Derwin, 1990).

In order to lift the barbell, the athlete performs work against gravity, causing a proportional change in the barbell's gravitational potential and kinetic energies (Garhammer, 1979, 1980, 1982, 1993). The changes in the barbell's gravitational potential and kinetic energies are proportional to its mass ( $m$ ), the acceleration of gravity ( $g$ ), and changes in height ( $h$ ) and velocity ( $v$ ). The mathematical relationship between work performed on the barbell ( $W_{Barbell}$ ) and its changes in gravitational potential and kinetic energies is presented in equation 1.

$$W_{Barbell} = (mg\Delta h) + \left(\frac{1}{2}m\Delta v^2\right) \quad (1)$$

Since barbell mass and gravitational acceleration is constant during a lift, the work performed on the barbell causes a proportional change in its velocity and height. When the athlete stops performing work on the barbell at the end of the pull, the barbell travels vertically as it loses kinetic energy and gains gravitational potential energy (Garhammer, 1980). Raising the barbell to a greater peak height thus requires more work to be performed on it during the pull. However, the goal of competitive weightlifting is to lift the greatest mass. Rearranging

equation 1 to solve for the mass lifted shows that this mass is proportional to the work performed on the barbell, while inversely proportional to its changes height and velocity (equation 2).

$$m = \frac{W}{(g\Delta h + \frac{1}{2}\Delta v^2)} \quad (2)$$

In order to lift the greatest mass relative to the work performed, which may be theorized as mechanically effective, weightlifters should only lift the barbell to the height and with the velocity strictly necessary to successfully complete the lift (Kipp & Harris, 2015). In contrast, lifting the barbell with maximal effort could be hypothesized to cause a greater than necessary change in the barbell's height and velocity, and thus, be theorized as less effective.

The ankle plantar flexors, knee extensors, and hip extensors are primarily responsible for the work performed on the barbell during the pull of the clean (Garhammer, 1982). Increasing the barbell mass during both the clean and back squat, causes a disproportionate increase in net joint moments (NJM), NJM work, and relative muscular effort (RME) at the ankle and hip, compared to the knee (Bryanton, Kennedy, Carey, & Chiu, 2012; Flanagan & Salem, 2008; Kipp, Harris, & Sabick, 2011). Since increasing the barbell's height or velocity requires greater work to be performed on it (equation 1), it may be hypothesized that a disproportionate increase in ankle plantar flexor and hip extensor joint mechanical efforts also occurs if greater effort is exerted during the pull. Any changes in load distribution could affect both inter-muscular coordination and the adaption of specific muscles to the clean. In order to better understand the relation between a mechanically effective technique and the neuromechanical demands required, a biomechanical comparison of cleans performed with different effort is warranted.

The purposes of this research were 1) to compare work performed on the barbell, and 2) work performed about the ankle, knee, and hip during the pull of minimal height, maximal effort, and power cleans. We hypothesized that the minimal height clean would require less

work to be performed on the barbell compared to the maximal effort and power cleans. Further, we hypothesized that the minimal height clean would require less work to be performed about the lower extremity joints compared to maximal effort and power cleans. Specifically, smaller hip extensor and ankle plantar flexor work were hypothesized to account for a smaller total work performed during minimal height clean. To provide further insight to the effects of exerting different effort during the pull, ankle, knee, and hip NJM and angles were also compared between conditions.

## **Methods**

### ***Participants***

Eight males and two females volunteered to participate in the study. Basic power calculations suggested that a sample size of 10 would allow for detection of within-subject differences of 0.5 standard deviations (SD) with a power of 0.80 at  $\alpha$ -level 0.05. To be included, participants had to be between 18 and 50 years old, and have at least one year's experience performing the clean. Participants were excluded if they did not display a toward-away-toward barbell trajectory similar to those found consistent among skilled weightlifters (Garhammer, 1985; Kauhanen, Häkkinen, & Komi, 1984). Ethical approval was obtained from a University of Alberta Research Ethics Board (Study ID: Pro00057564), and all participants provided written informed consents prior to participation. Participant 3 and 5 were excluded based on their barbell trajectories. Characteristics of the remaining eight participants are shown in Table 1.

Table 1. Participant characteristics.

<b>Participant</b> ( <i>n</i> )	<b>Sex</b> ( <i>M/F</i> )	<b>Age</b> ( <i>years</i> )	<b>Stature</b> ( <i>m</i> )	<b>Mass</b> ( <i>kg</i> )	<b>1 RM clean</b> ( <i>kg</i> )	<b>Experience</b> ( <i>years</i> )
1	F	28	1.67	67.5	77.5	5
2	M	19	1.82	99.5	125.0	3
4	M	20	1.70	67.8	105.0	3
6	M	25	1.89	95.6	140.0	4
7	M	32	1.85	108.8	110.0	3
8	M	36	1.79	117.0	150.0	16
9	M	25	1.70	80.8	115.0	8
10	F	22	1.68	111.5	130.0	3
<b>Mean</b>	-	26	1.76	93.6	119.1	6
<b>SD</b>	-	6	0.09	19.5	22.6	5

*M* = Male, *F* = Female, 1 RM = One repetition maximum

### **Procedures**

Participants completed two test sessions with minimum 72 h between them. In the first, the participants' one repetition maximum (1 RM) clean was established while barbell trajectories were obtained as described by Dæhlin et al. (Appendix A). All warm-up lifts and 1 RM attempts were recorded with a digital camera (D3200, Nikon, Tokyo, Japan) used in video recording mode with 1280 by 720 pixel resolution capturing 60 frames per second. The 15-55 mm variable lens was set to maximum zoom and the aperture, shutter speed and ISO was set to 5.6,  $1 \cdot 500^{-1}$  s and 800, respectively. The optical axis of the camera was positioned 0.80 m above the ground at a distance of 15 m from the right end of the barbell (Olympic competition bar, Iron Grip, Santa Ana, CA, USA), capturing the lifts in a sagittal plane view. An LED-marker was placed on the right end of the barbell.

Participants performed a self-selected warm-up resembling their competition warm-up before the test. Increments in barbell mass was decided by the participants and rest was provided *ad libitum* between attempts. All participants reached their 1 RM within 2 to 4 attempts with a barbell load greater than 90% 1 RM. Participants completed a familiarization to the three test conditions after their 1 RM was established.

During the second session, participants performed the minimal height, maximal effort, and power cleans while being recorded with a three-dimensional (3D) motion analysis

system. First, participants performed a self-selected warm-up consisting of stretches, unloaded squats, and cleans with an unloaded barbell. Next, one investigator instrumented the participants with retro-reflective skin markers (12 mm in diameter). A six-degree of freedom marker set described by Chiu and Salem (2006) was used (Figure 1). Briefly, the marker set consisted of 17 calibration markers defining proximal and distal segment ends, and tracking clusters of 3 and 4 markers (feet and legs/thighs, respectively) affixed to moulded thermoplastic plates. The proximal calibration markers on the pelvis also served as tracking markers. The barbell was instrumented with one retro-reflective marker on each barbell end.

Participants then performed a clean specific warm-up consisting of 1 set of 3 repetitions (one per condition) at barbell loads of 30, 50, and 70% 1 RM. After completing the warm-up, 4 sets of 1 repetition in each condition was performed with a barbell load of 80% 1 RM. This load was chosen because biomechanical parameters and technique is known to stabilize around 80% 1 RM (Lukashev, Medvedev, & Melkonian, 1979). The order of the three conditions was randomized. One set was completed in each condition before the next set was initiated. 2-4 min of inter-set rest was allowed to minimize fatigue. Seven optoelectronic cameras (ProReflex MCU240; Qualisys, Gothenburg, Sweden) sampling at 120Hz was used to record marker trajectories, while ground reaction forces (GRF) was measured using two force plates (OR6-6, AMTI, Watertown, MA, USA) sampling at 1200Hz. All data was collected using Qualisys Track Manager (Version 2.4.546). The reliability of joint angle and joint moment data ( $ICC > 0.9$ ) has previously been established for the described methods and marker set (Chiu & Salem, 2006). All successful trials were used in data analysis.



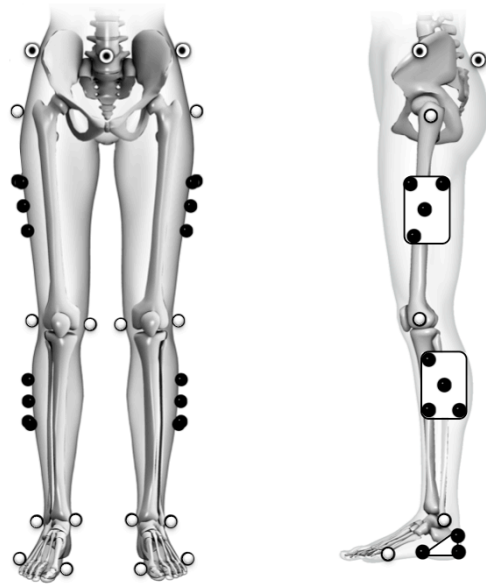


Figure 1. Frontal (left panel) and sagittal (right panel) view of the calibration (white) and tracking (black) markers used in the present study. White markers with a black dot served as both calibration and tracking markers. The foot cluster markers are not visible in the frontal plane view.

### ***Data processing and reduction***

Tracker (Version 4.91; <http://physlets.org/tracker/>; accessed October 6, 2015) was used to automatically track the LED-marker's trajectory as described by Dæhlin et al. (Appendix A). Briefly, the calibration stick, coordinate system origin, and LED-marker were manually identified two frames prior to lift-off, after which the marker was automatically tracked until two frames past its lowest vertical position during the squat under the barbell. Horizontal and vertical position coordinates were smoothed using a 5-point moving arc polynomial (Wood, 1982).

Visual 3D (Version 5.00; C-Motion, Germantown, MD) was used to create a rigid-link model. Seven rigid segments represented the pelvis and both thighs, legs, and feet, respectively. Marker and force data were filtered using a zero-lag 4<sup>th</sup> order low-pass

butterworth filter with an 8 Hz cut-off frequency. This cut-off frequency was chosen based on a residual analysis and visual inspection of segment centre of mass (COM) acceleration time-curves. Segment and laboratory coordinate systems conformed to the right hand rule with the Z-axis pointing superiorly and Y-axis pointing anteriorly. Segment angles were calculated relative to the laboratory coordinate system using a ZYX Cardan sequence (Baker, 2001). Joint angles were calculated as orientations of the proximal relative to the distal segment using an XYZ Cardan sequence (Grood & Suntay, 1983). Inverse dynamics was used to calculate ankle, knee, and hip NJMs, which were expressed in the coordinate system of the distal segment. Segments' inertial properties and COM was determined based on segments having the shape of conical frusta, and mass relative to total body mass was determined from anthropometric data (Dempster, 1955). NJM work was computed as the time-integral of net joint power. The barbell was represented as a point mass by averaging the position of the barbell end markers. Work performed on the barbell was computed by summing its changes in gravitational potential and kinetic energies. These energy changes were computed as the product of the barbell's mass, the acceleration of gravity, and change in barbell height, and as the product of the barbell's mass and change in velocity squared, divided by two, respectively (Garhammer, 1993). All variables were computed from lift-off until the first peak knee extension (first pull), from the first peak knee extension until the second peak knee flexion (transition phase), and from the second peak knee flexion until peak barbell velocity (second pull). Work performed was summed over the first pull, transition, and second pull phases to represent the total pull. Segment kinematics was averaged across legs, while kinetics was summed between legs. All joint kinetics were normalized to body mass, while changes in barbell height were normalized to stature and expressed as a percentage.

### ***Statistical analysis***

Statistical analyses were conducted in SPSS v21.0 (SPSS Inc., Chicago, IL). One-way repeated-measures ANOVAs were used to compare the changes in barbell height, kinetic and gravitational potential energies, work performed on the barbell, and total NJM work between the conditions. Multivariate repeated-measures ANOVAs, using ankle plantar flexors, knee extensors, knee flexors, and hip extensors as multivariate levels, were used to compare the work performed at the ankle, knee and hip joint between conditions. For NJM and joint angles, the ankle, knee, and hip was used as multivariate levels. Univariate ANOVAs were only considered if the multivariate main effect was significant using Wilk's  $\lambda$ . When univariate ANOVAs were significant, multiple t-tests with Bonferroni correction were used for *post hoc* comparisons. The data were normally distributed, and sphericity was tested using Mauchly's test of sphericity. When the sphericity assumption was violated, Greenhouse-Geisser corrections were used. Means  $\pm$  SD and Cohen's *d* effect sizes (ES) are reported. The level of significance was set *a priori* to 0.05.

### **Results**

All included participants displayed a towards-away-towards barbell trajectory during the 1 RM test (Figure 2). Peak barbell height was smaller during the minimal height clean ( $65.1 \pm 2.8\%$ ) compared to the maximal effort ( $68.6 \pm 1.7\%$ ;  $P = 0.02$ ; ES = 1.4) and power cleans ( $68.9 \pm 2.2\%$ ;  $P > 0.01$ ; ES = 2.0). Peak barbell height did not differ significantly between the maximal effort and power cleans ( $P > 0.05$ ; ES = 0.4).



Figure 2. A representative barbell trajectory from the 1 RM clean test. Positive values indicate anterior and superior.

Total work performed on the barbell was smaller during the minimal height clean ( $8.66 \pm 1.32 \text{ J}\cdot\text{kg}^{-1}$ ) compared to the maximal effort ( $9.13 \pm 1.40 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.04$ ;  $ES = 1.3$ ) and power cleans ( $9.25 \pm 1.28 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.01$ ;  $ES = 1.5$ ), as illustrated in Figure 3. When breaking down the pull into phases, the work performed on the barbell during the second pull was smaller in the minimal height clean ( $2.81 \pm 0.75 \text{ J}\cdot\text{kg}^{-1}$ ) compared to the power clean ( $3.21 \pm 0.90 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.03$ ;  $ES = 1.2$ ). No significant differences were found between the maximal effort and power cleans in any phase of the lift ( $P > 0.05$ ).

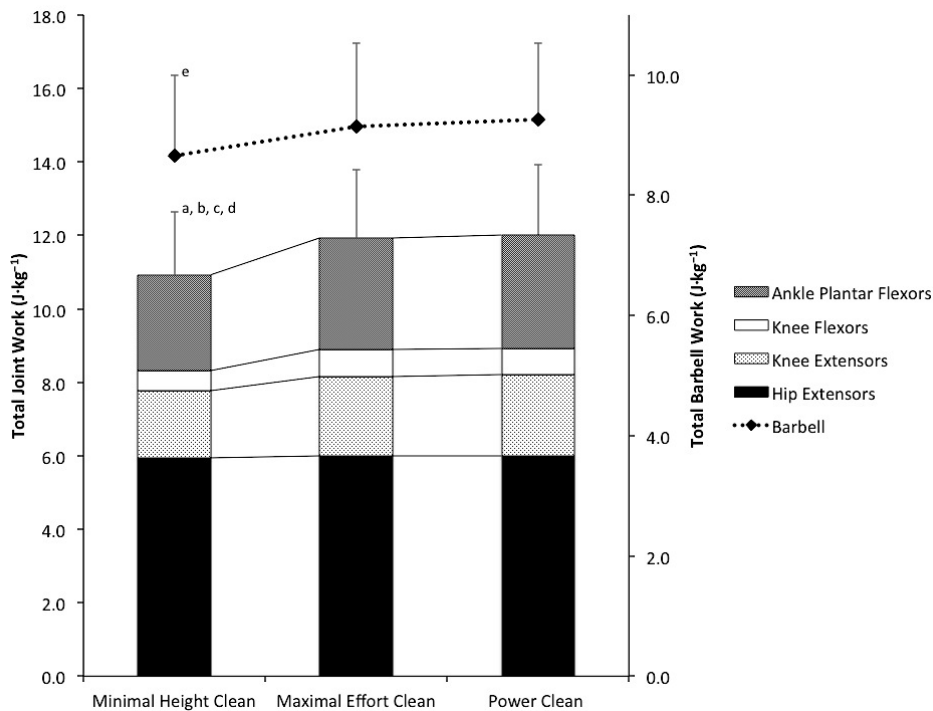


Figure 3. The stacked bars show the total work performed about the lower extremity joints, and the diamonds indicate the total work performed on the barbell during the entire pull of the minimal height, maximal effort and power cleans.

<sup>a</sup>Total NJM joint work: Minimal height < Maximal effort & Power clean

<sup>b</sup>Knee NJM extensor work: Minimal height < Maximal effort & Power clean

<sup>c</sup>Knee NJM flexor work: Minimal height < Maximal effort & Power clean

<sup>d</sup>Ankle plantar flexor NJM work: Minimal height < Power clean

<sup>e</sup>Barbell work: Minimal height < Maximal effort & Power clean

The total NJM work performed about the lower extremity joints was strongly correlated to the work performed on the barbell in the minimal height clean ( $r = 0.97$ ,  $P < 0.01$ ), maximal effort clean ( $r = 0.95$ ,  $P < 0.01$ ), and power clean ( $r = 0.94$ ,  $P < 0.01$ ). Total NJM work was smaller during the minimal height clean ( $10.9 \pm 1.7 \text{ J}\cdot\text{kg}^{-1}$ ) compared to the maximal effort ( $12.0 \pm 1.8 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.03$ ; ES = 1.2) and power cleans ( $12.0 \pm 1.9 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.02$ ; ES = 1.3), as illustrated in Figure 3. A significant multivariate main effect (Wilk's  $\lambda = 0.010$ ) indicated that NJM work performed at the individual lower extremity joints differed (Figure 3). Univariate and *post hoc* tests revealed that both total knee extensor and knee flexor

NJM work was smaller during the minimal height clean ( $1.8 \pm 0.5 \text{ J}\cdot\text{kg}^{-1}$  and  $0.6 \pm 0.2 \text{ J}\cdot\text{kg}^{-1}$ , respectively) compared to the maximal effort ( $2.2 \pm 0.7 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.03$ ; ES = 1.1 and  $0.7 \pm 0.3 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.01$ ; ES = 1.7, respectively) and power cleans ( $2.2 \pm 0.7 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.01$ ; ES = 1.5 and  $0.7 \pm 0.3 \text{ J}\cdot\text{kg}^{-1}$ ;  $P < 0.01$ ; ES = 2.6, respectively). Moreover, total ankle plantar flexor NJM work was smaller during the minimal height clean ( $2.6 \pm 0.5 \text{ J}\cdot\text{kg}^{-1}$ ) compared to the power clean ( $3.1 \pm 0.5 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.03$ ; ES = 1.3), whereas it tended to be significantly smaller compared to the maximal effort clean ( $3.0 \pm 0.6 \text{ J}\cdot\text{kg}^{-1}$ ;  $P = 0.06$ ; ES = 1.1). The total hip extensor NJM work did not differ ( $P > 0.05$ ) between the minimal height ( $6.0 \pm 1.3 \text{ J}\cdot\text{kg}^{-1}$ ), maximal effort ( $6.0 \pm 1.4 \text{ J}\cdot\text{kg}^{-1}$ ), or power cleans ( $6.0 \pm 1.5 \text{ J}\cdot\text{kg}^{-1}$ ). The differences in knee flexor NJM work occurred during the transition phase, whereas differences in knee extensor NJM work occurred during the second pull ( $P < 0.05$ ; Table 2). The differences in ankle plantar flexor NJM work were also confined to the second pull ( $P < 0.05$ ; Table 2), whereas no differences in NJM work occurred during the first pull ( $P > 0.05$ ; Table 2).

Table 2. Ankle plantar flexor, knee extensor, knee flexor and hip extensor NJM work performed in the 1<sup>st</sup> pull, transition, and 2<sup>nd</sup> pull phases of the minimal height, maximal effort and power cleans.

		<b>Minimal height clean</b>	<b>Maximal effort clean</b>	<b>Power clean</b>
<i>1<sup>st</sup> pull phase:</i>				
Ankle plantar flexor work	(J·kg <sup>-1</sup> )	1.11 ± 0.20	1.15 ± 0.24	1.18 ± 0.22
Knee extensor work	(J·kg <sup>-1</sup> )	0.93 ± 0.19	0.95 ± 0.19	0.98 ± 0.14
Knee flexor work	(J·kg <sup>-1</sup> )	0.25 ± 0.12	0.31 ± 0.16	0.33 ± 0.16
Hip extensor work	(J·kg <sup>-1</sup> )	3.11 ± 0.94	3.05 ± 0.96	3.08 ± 0.95
<i>Transition phase:</i>				
Ankle plantar flexor work	(J·kg <sup>-1</sup> )	0.39 ± 0.06	0.45 ± 0.11	0.45 ± 0.08
Knee extensor work	(J·kg <sup>-1</sup> )	0.13 ± 0.17	0.13 ± 0.16	0.14 ± 0.17
Knee flexor work <sup>a,b</sup>	(J·kg <sup>-1</sup> )	0.26 ± 0.05	0.39 ± 0.11	0.36 ± 0.09
Hip extensor work <sup>c</sup>	(J·kg <sup>-1</sup> )	1.78 ± 0.54	1.83 ± 0.57	1.91 ± 0.62
<i>2<sup>nd</sup> pull phase:</i>				
Ankle plantar flexor work <sup>b</sup>	(J·kg <sup>-1</sup> )	1.11 ± 0.33	1.43 ± 0.37	1.44 ± 0.37
Knee extensor work <sup>a,b</sup>	(J·kg <sup>-1</sup> )	0.78 ± 0.43	1.08 ± 0.54	1.09 ± 0.49
Knee flexor work	(J·kg <sup>-1</sup> )	0.03 ± 0.05	0.04 ± 0.07	0.04 ± 0.07
Hip extensor work	(J·kg <sup>-1</sup> )	1.06 ± 0.58	1.11 ± 0.45	1.04 ± 0.57

<sup>a</sup>Minimal height clean < Maximal effort clean ( $P < 0.05$ )

<sup>b</sup>Minimal height clean < Power clean ( $P < 0.05$ )

<sup>c</sup>Significant univariate ANOVA ( $P < 0.05$ ) without significant post hoc comparisons ( $P > 0.05$ ).

Peak ankle, knee, or hip NJM did not differ between the conditions in any phases of the pull ( $P > 0.05$ ; Table 3). In contrast, knee flexion angles were smaller at the end of the transition phase in the minimal height clean compared to the maximal effort and power cleans ( $P < 0.05$ ; Table 4). During the second pull, ankle plantar flexion and hip extension angles were smaller during the minimal height clean compared to the maximal effort and power cleans ( $P < 0.05$ ; Table 4), whereas knee extension angles were only smaller during the minimal height clean compared to the maximal effort clean ( $P < 0.05$ ; Table 4).

Table 3. Peak ankle, knee, and hip net joint moments (NJM) during the 1<sup>st</sup> pull, transition and 2<sup>nd</sup> pull phases. Positive values indicate ankle plantar flexor, knee extensor and hip extensor moments, respectively.

Phase		Minimal Height Clean	Maximal Effort Clean	Power Clean
<i>1<sup>st</sup> Pull:</i>				
Ankle NJM	(N·m)	1.49 ± 0.23	1.50 ± 0.26	1.54 ± 0.25
Knee NJM	(N·m)	1.08 ± 0.13	1.09 ± 0.08	1.13 ± 0.07
Hip NJM	(N·m)	2.94 ± 0.37	3.03 ± 0.43	3.04 ± 0.43
<i>Transition:</i>				
Ankle NJM	(N·m)	0.76 ± 0.31	0.78 ± 0.18	0.74 ± 0.18
Knee NJM	(N·m)	- 0.79 ± 0.19	- 0.90 ± 0.21	- 0.89 ± 0.17
Hip NJM	(N·m)	2.51 ± 0.30	2.56 ± 0.35	2.59 ± 0.44
<i>2<sup>nd</sup> Pull:</i>				
Ankle NJM	(N·m)	1.81 ± 0.20	1.88 ± 0.21	1.86 ± 0.19
Knee NJM	(N·m)	1.14 ± 0.32	1.24 ± 0.24	1.38 ± 0.32
Hip NJM	(N·m)	1.83 ± 0.45	1.88 ± 0.46	1.78 ± 0.58

Table 4. Ankle, knee and hip angles at lift-off, the first peak knee extension, second peak knee flexion, and peak barbell velocity. Positive values indicate ankle plantar flexion, knee flexion and hip extension, respectively.

Event		Minimal Height Clean	Maximal Effort Clean	Power Clean
<i>Lift-off:</i>				
Ankle	(°)	- 29 ± 4	- 30 ± 5	- 30 ± 4
Knee	(°)	93 ± 9	94 ± 8	94 ± 7
Hip	(°)	- 100 ± 8	- 100 ± 8	- 100 ± 8
<i>1<sup>st</sup> Peak knee extension:</i>				
Ankle	(°)	- 6 ± 3	- 5 ± 2	- 5 ± 2
Knee	(°)	33 ± 7	31 ± 6	32 ± 7
Hip	(°)	- 66 ± 5	- 67 ± 5	- 67 ± 6
<i>2<sup>nd</sup> Peak knee flexion:</i>				
Ankle	(°)	- 17 ± 3	- 18 ± 3	- 18 ± 3
Knee <sup>a,b</sup>	(°)	52 ± 10	56 ± 10	56 ± 10
Hip	(°)	- 41 ± 10	- 44 ± 6	- 42 ± 8
<i>Peak barbell velocity:</i>				
Ankle <sup>a,b</sup>	(°)	7 ± 5	15 ± 6	15 ± 7
Knee <sup>a</sup>	(°)	22 ± 6	17 ± 7	18 ± 7
Hip <sup>a,b</sup>	(°)	- 5 ± 7	0 ± 4	- 1 ± 4

<sup>a</sup>Minimal height clean < Maximal effort clean ( $P < 0.05$ )

<sup>b</sup>Minimal height clean < Power clean ( $P < 0.05$ )

## Discussion

The purpose of this research was to compare the mechanical work performed on the barbell and about the lower extremity joints between the minimal height, maximal effort, and power



cleans. The minimal height clean required less work to be performed on the barbell and about the lower extremity joints during the transition and second pull phases in order to lift the barbell to a lesser peak height. The smaller total lower extremity NJM work was primarily accounted for by smaller knee extensor and knee flexor work.

A mechanically effective technique may be regarded as a technique that allows the largest mass to be successfully lifted relative to the work performed on it. Such a lifting technique is therefore dependent on minimizing work performed that is not essential to the success of the lift. Some have suggested that this may be achieved by avoiding accelerating the barbell more in the pull than what is strictly necessary to successfully complete the lift (Derwin, 1990; Kipp & Harris, 2015). Others have purported that it may be achieved by minimizing peak barbell height (Isaka, Okada, & Funato, 1996). In the present study, participants performed less work on the barbell during the pull of the minimal height clean compared to the maximal effort and power cleans, and therefore elevated it to a smaller peak height. The minimal height clean may therefore be interpreted as more effective compared to the other two variations. Moreover, it appears that the minimal height clean resemble the technique used by elite weightlifters, as they elevate the barbell to a lesser height compared to their less skilled counterparts (Burdett, 1982; Garhammer, 1993; Gourgoulis et al., 2002; Kauhanen et al., 1984). As a smaller peak height allows less time for the athlete to reposition under the barbell, it is not surprising that the squat under the barbell is executed faster in elite weightlifters compared to their less skilled counterparts (Häkkinen, Kauhanen, & Komi, 1984; Kauhanen et al., 1984). Similarly, the minimal height clean forces the athlete to perform a faster squat under the barbell due to a smaller peak barbell height. Therefore, it may be used to train this aspect of the lift, which is considered paramount to weightlifting performance (Burdett, 1982; Häkkinen et al., 1984; Kauhanen et al., 1984).

The smaller work performed on the barbell was accompanied by a smaller NJM work performed about the lower extremity joints. The strong correlation between work performed on the barbell, and total NJM work performed about the lower extremity joints supports the notion that lower extremity muscle strength is important for weightlifting success (Garhammer, 1982). In contrast to our hypotheses, the smaller total NJM work performed during the minimal height clean was primarily accounted for by smaller NJM work performed by the knee flexors in the transition and knee extensors during the second pull. This was unexpected since previous research has found ankle plantar flexor and hip extensor NJM, NJM work, and RME to increase disproportionately with increasing load (Bryanton et al., 2012; Flanagan & Salem, 2008; Kipp et al., 2011). However, by affecting either NJMs or joint excursion range, alterations in segment kinematics, centre of pressure, or GRF magnitude may affect the NJM work performed about a joint (Flanagan & Salem, 2008). In the present study, no differences were found in peak ankle, knee, or hip NJM between conditions. In contrast, some joint kinematics differed during the transition and second pull. Specifically, knee flexion angles were smaller at the end of the transition phase in the minimal height clean compared to the maximal effort and power cleans, whereas no differences in joint angles were present at the end of the first pull. This difference in knee joint excursion may therefore explain the smaller knee flexor NJM work performed during the transition phase. Elite male weightlifters have been found to flex their knee by approximately 20° during the transition phase (Bartonietz, 1996; Gourgoulis, Aggelousis, Mavromatis, & Garas, 2000; Gourgoulis et al., 2002), which is highly comparable with that of the minimal height clean (20°) in the present study. In contrast, participants flexed their knees by 25° during the transition of both the maximal effort and power cleans. This larger knee flexion may be unfavourable, as more skilled weightlifters have been found to flex their knees less than their less skilled counterparts during the transition phase (Burdett, 1982). Moreover, male

weightlifters, which lift a greater mass relative to their body mass than females, are more extended at the knee at the end of the transition phase compared with female weightlifters (Harbili, 2012).

In the second pull, participants plantar flexed their ankles less, and extended their knees and hips less in the minimal height clean compared to the maximal effort and power cleans. As no differences in peak ankle, knee, and hip NJM was present in the second pull, it appears that also the smaller knee extensor and ankle plantar flexor NJM work performed during the second pull of the minimal height clean was a result of differences in joint kinematics between conditions. Although the ankle plantar flexor NJM work did not differ significantly between the minimal height clean and maximal effort clean, the effect size of 1.1 indicates that a practically meaningful difference in ankle plantar flexor NJM work occurred also between the minimal height and maximal effort cleans. At first glance, a less extended position at the end of the second pull may seem counterintuitive. However, a previous study found that more skilled weightlifters are more dorsi flexed at the ankle, and flexed at the knee and hip at the end of the second pull, when compared to less skilled weightlifters (Burdett, 1982). Moreover, peak knee and hip angles during second pull of the minimal height clean resemble those reported for elite calibre weightlifters (Gourgoulis et al., 2000; Gourgoulis et al., 2002). In contrast, these joints were more extended at the end of the second pull in the maximal effort and power cleans. One may hypothesize that a more flexed position at the ankle, knee, and hip facilitates the fast squat under the barbell. Moreover, the differences in joint kinematics between conditions may account for the discrepancies in load distribution between current and previous findings (Bryanton et al., 2012; Flanagan & Salem, 2008; Kipp et al., 2011).

Weightlifters may perform the clean and its variations to improve strength or perfect lifting technique. Considering the large volume of squats and pulls included in weightlifting

training programs (Stone, Pierce, Sands, & Stone, 2006b), the latter appears to be the primary purpose of including clean variations in competitive weightlifters' training programs. The results of the present investigation revealed that the minimal height clean allowed a barbell of the same mass to be lifted more effectively, with barbell and joint kinematics that resemble those of elite weightlifters more closely compared to the maximal effort and power cleans. Therefore, the minimal height clean may be used for the purpose of perfecting a mechanically effective technique, which resembles the technique used by elite weightlifters. In contrast, the maximal effort and power cleans requires more work to be performed by the knee extensors and knee flexors during the pull, which may be beneficial for specific strength training of these muscle groups. However, the maximal effort clean does not appear to provide any additional benefit compared to performing the power clean, as no differences were found between these conditions. Therefore we recommend that the power clean is included in weightlifting training programs, whereas this research does not provide any justification for including the maximal effort clean.

Although this research provides novel insight to the kinetic and kinematic differences between cleans performed with different effort, some limitations warrant discussion. Firstly, the desired number of participants was not met due to difficulties in recruiting participants who displayed a toward-away-toward barbell trajectory. However, *post hoc* power calculations revealed statistical powers in excess of 0.90 for the primary outcome variables. Thus, the low number of participants does not appear to have compromised our results. Secondly, only a single barbell load was investigated in the present study, and the results can therefore not be generalized to the entire load spectrum. Future research should investigate how performing the clean with different effort affects its biomechanics across the load spectrum. Lastly, the filter cut-off used was not optimal for filtering GRFs. However, filtering data at different cut-off frequencies have been shown to introduce artefacts, and should be

avoided (Kristianslund, Krosshaug, & van den Bogert, 2012). Since computations of NJM are dependent on accurate accelerations of the segments' COM, the cut-off frequency was determined based on our marker data, as recommended (Kristianslund et al., 2012).

### **Conclusions**

The minimal height clean allows the same barbell mass to be lifted by performing less work on the barbell and about the lower extremity joints compared to the maximal effort and power cleans. The smaller total NJM work was primarily accounted for by less knee flexor and knee extensor NJM work in the transition phase and second pull, respectively. Moreover, there were no differences between the maximal effort and power cleans.

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## List of Figures

**Figure 2.1:** The clean may be divided into six phases based on seven different key positions. The barbell trajectory of the recovery phase is not shown in the figure, but may be expected to be close to vertical.

**Figure 3.1:** A graph of residuals (thick black line) plotted against different cut-off frequencies. The dashed line indicates the noise removed at different cut-off frequencies, while the thin gray line indicates the level of noise present in the data. The residuals rising above the gray line represents signal distortion.

**Figure 3.2:** Illustration of a Cartesian coordinate used for two-dimensional (panel a) or three-dimensional (panel b) analysis. In panel a, the Z-axis may be imagined to be pointing straight out of the picture.



## Abbreviations

1 RM	One repetition maximum
2-D	Two-dimensional
3-D	Three-dimensional
COM	Center of mass
ES	Effect size
GRF	Ground reaction force
NJM	Net joint moment
RME	Relative muscular effort
SD	Standard deviation

## List of Appendices

- Appendix A      Manuscript: “Enhancing Digital Video Analysis of Bar Kinematics in Weightlifting: A Case Study”. The manuscript disseminates the results from a pilot study conducted in conjunction with this thesis, and is currently under consideration with the Journal of Sport Sciences. 26 pages.
- Appendix B      Letter from the Research Ethics Board: “Notification of approval”. The letter confirming that ethical approval for the thesis research project was given. 1 page.
- Appendix C      Letter to participants: “Letter of information”. The information letter that was given to potential participants. 1 page.
- Appendix D      Form: “Informed consent form”. The consent form participants completed prior to participation. 1 page.
- Appendix E      Flyer: “Olympic weightlifting study”. A flyer used for recruitment purposes. 1 page.

**Enhancing Digital Video Analysis of Bar Kinematics in Weightlifting: A Case Study**

Running title: Enhancing Digital Video Analysis of Weightlifting

Laboratory: Sports Biomechanics Laboratory, Faculty of Physical Education and Recreation,  
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**ABSTRACT**

Weightlifting technique can be objectively assessed from two-dimensional video recordings. Despite its importance, participants' bar trajectories in research involving the snatch or clean exercises are often not reported, potentially due to the time required to digitize video. The purpose of this investigation was to evaluate the use of an LED-based marker, digital video and open source software to automatically track the bar end during weightlifting exercises. A former national-level weightlifter was recorded with a digital video camera performing the snatch, clean and jerk, and squat exercises. An LED-based marker was placed on the right end of the bar. This marker was automatically tracked using two open source software programs to obtain vertical and horizontal position coordinates. The LED-based marker was successfully auto-tracked for all videos, over a variety of camera settings. Further, the vertical and horizontal bar displacements, and vertical bar velocity were consistent between the two software programs. The present study demonstrates that an LED-based marker can be automatically tracked using open source software. This combination of an LED-based marker, consumer camera and open source software is an accessible, low cost method to objectively evaluate weightlifting technique.

## INTRODUCTION

In addition to being events in competitive weightlifting, it is purported that performing the snatch, clean & jerk, and their variations will enhance performance of tasks requiring high rates of force development, such as jumping (14). The effectiveness of weightlifting exercises for this purpose may be due to the similar shape of ground reaction force pattern in weightlifting exercises and jumping (9). Specifically, a high ground reaction force impulse is generated using an inverted “U” as opposed to an inverted “V” shaped ground reaction force pattern in both exercises (9). Recently, weightlifting exercises have also been proposed as a training modality to enhance performance during impact, such as landing from a jump (21). This recommendation is due to joint kinematic and kinetic similarities between jump landings and the receiving phase of cleans and power cleans (21). Due to their potential for improving sports performance, weightlifting exercises are increasingly used in strength training programs.

The increased interest in weightlifting variations as training modalities has been accompanied by more investigations on these exercises. Although there are some general kinematic and kinetic characteristics for both the snatch and clean, variations of performing these exercises are possible, such as those distinguished by the lifters’ bar trajectory (22). The bar trajectories displayed during the snatch and clean has been found to be consistent for world and Olympic caliber weightlifters across several decades of competition. Specifically, the bar has a posterior translation during the first pull, moving towards the lifter (7, 11, 17, 24). During the second pull, the bar has a small anterior translation, moving away from the lifter (7, 11, 17, 24). Following the second pull, the bar has a second posterior translation (7, 24). The most common deviation from this characteristic bar trajectory is anterior bar translation during the first pull, which is considered a technical fault (24). This fault is often accompanied with net anterior displacement of the bar where the bar is forward of the starting

position when caught overhead or on the shoulders. Unsuccessful lifts are commonly the result of net anterior translation (24). Another key technique parameter is the height to which the bar is raised. In elite weightlifters, peak vertical bar displacement is approximately 60% and 50% of the lifter's stature for the snatch and clean, respectively (2, 23). Utilizing these parameters, researchers and coaches could objectively, rather than subjectively, evaluate an athlete's technique.

How the snatch and clean are specifically executed may influence the weight lifted, training response, and injury potential. Despite being important for interpreting results, characteristics describing an individual's technique, such as bar trajectory or peak vertical displacement, are often not reported in weightlifting research studies. Some studies report that a weightlifting coach judged the participants' technique, however, the specific technical characteristics are not detailed (e.g. 18). More often, studies do not provide any detail regarding the participants' technique, particularly in studies that investigate non-weightlifters (e.g. 14). In principle, objectively measuring technical proficiency using kinematic parameters should be feasible for both researchers and practitioners, given the availability of equipment that can be used to obtain bar displacement data.

Recent biomechanical studies have employed three-dimensional motion analysis (21) or linear position transducers (5); these technologies would allow bar kinematics to be assessed. However, these technologies require expensive equipment and specialized software that may not be available outside of a biomechanics laboratory. An alternative is digital video; the proliferation of consumer devices with digital video makes this technology widely available for both researchers and coaches. Several inexpensive or open source software programs are also available to analyze digital video (10). Some open source software programs include the capability to auto-track objects, where a pattern distinctive from the surrounding image can be tracked over multiple frames. Coloured tape and reflective markers

have been used to facilitate auto-tracking (10). However, we have found that these techniques do not create a sufficiently distinctive pattern compared to the surrounding image to be auto-tracked.

An alternative method to create a distinctive pattern is the use of light emitting diodes (LED). A benefit of LEDs is that they emit light rather than reflect it, and thus focus more energy on the camera's sensor to create a distinctive pattern. LEDs have previously been used in biomechanics research. However, these methods have required either or both specialized hardware and software, which limits their availability. The purpose of this research was to evaluate the ability to automatically track an LED-based marker recorded with digital video using open source software to assess bar kinematics in weightlifting. A specific goal was to maximize the accessibility of this method; therefore, a consumer camera, open source software, and standard spreadsheet software were used.

## **METHODS**

### Experimental approach to the problem

One participant was recorded using two-dimensional video during an exercise session. The participant performed multiple sets of the snatch, clean & jerk, and back squat as detailed in Table 1. The squat lifts were included to evaluate the applicability of the method to bar lifts other than the competition exercises in weightlifting. Bar trajectories were obtained from the digital videos using the auto-tracking function in open source software. To facilitate auto-tracking, an LED-based marker was placed on the right bar end. Different software packages, smoothing and filtering, and repeated digitizations were compared.

\*\*\*Table 1 about here\*\*\*

## Subjects

One of the authors, a former Canadian national-level weightlifter, participated in the study. The lifter was 36 years old, 1.78 m tall and 115 kg body mass. His recent one repetition maximums (1 RM) were 120 kg in the snatch and 140 kg in the clean and jerk. The study was approved by a Research Ethics Board at the University of Alberta (study ID: Pro00061284).

## Procedures

Digital video were recorded for all sets and repetitions performed during the exercise session. The camera was placed on a tripod to record a sagittal view at a distance of 15 m from the right end of the bar, with its optical axis 0.80 m above the ground. A Nikon D3200 camera with a 15-55 mm variable zoom lens was used in video recording mode with 1280 by 720 pixel resolution capturing 60 frames per second. The lens was set to maximum zoom and the widest aperture setting ( $f/5.6$ ) was used, however, shutter speed and ISO settings were varied for purposes of evaluating the image quality (Table 1). The videos were recorded in a room with fluorescent lighting. The video data were recorded to an SD card, and later transferred to a computer for analysis.

A laboratory-constructed LED-based marker was placed on the right end of the bar (Olympic competition bar, Iron Grip, Santa Ana, CA, USA; Figure 1). The marker consisted of five evenly spaced white LEDs that were powered by two coin cell batteries. The LED-based marker was affixed to a collar made of low-temperature thermoplastic to allow the marker to be placed on and removed from the bar with ease. The entire marker and collar assembly had a mass of 37 g. A wooden rod indicating 1 m was placed in the camera's field of view for calibration purposes (Figure 2).



\*\*\*Figure 1 & 2 about here\*\*\*

One investigator performed the auto-tracking procedure for all snatch, clean and squat repetitions using the open source software programs Tracker (<http://physlets.org/tracker/>; accessed October 6, 2015) and Kinovea ([www.kinovea.org](http://www.kinovea.org); accessed October 3, 2015). For reference length calibration, the ends of the wooden rod were digitized two frames prior to lift-off. In the same frame, the coordinate system origin was assigned to the location of the LED-based marker. Positive values indicate superior and anterior with respect to the lifter. The LED-based marker was manually digitized two frames prior to lift-off, after which, the software's automatic tracking feature was used to digitize the marker until two frames past the lowest bar height in the receiving phase. Horizontal and vertical position coordinates were exported in \*.xlsx file format. This procedure was performed on two separate occasions in both software programs. Two spreadsheet templates (Excel 2007, Microsoft Corporation, Redmond, WA) were developed to either smooth or filter the data. The smoothing template used a five-point moving arc to smooth position coordinates, and the first derivative of the five-point moving arc was used to calculate horizontal and vertical velocity, as described by Wood (25). The filtering template used a 4<sup>th</sup> order Butterworth filter with cut-off frequencies of 3 Hz for the horizontal (X) coordinates and 6 Hz for the vertical (Y) coordinates. These cut-offs were based on Fast Fourier transform which showed that 99% of the signal power was below these frequencies. The first derivative of the five-point moving arc was used to calculate horizontal and vertical velocity from the filtered data (25).

Peak vertical bar displacement, drop distance from peak vertical bar displacement to the lowest bar position in the receiving phase, peak vertical barbell velocity, and net horizontal displacement of the bar were extracted for comparisons of: 1) software programs, 2) smoothing versus filtering and 3) evaluation of intra-rater consistency. These variables

were selected because they are commonly used indicators of weightlifting technique (2, 7, 11, 12, 15, 17, 24). Additional, but less commonly used variables were also analyzed (Tables 2 and 3).

#### Statistical analyses

Mean and standard deviations (SD) are presented. Mean differences of each variable were compared between the different processing techniques. As only one participant was recorded, no further statistical procedures were appropriate to use.

## RESULTS

The time required to digitize and process all repetitions once was approximately 66 minutes or 2 minutes per repetition; both software programs required the same time. The LED-based marker could be automatically tracked for all videos, regardless of camera settings. Visual inspection while the LED-based marker was being auto-tracked found no instances where the software failed to identify the marker. Three of the camera settings provided sufficient image quality to see the LED marker, the entire meter stick, and the lifter (Panels A., B. and E., Figure 2)

Digitizing data in both software programs provided similar results, with mean differences of less than  $\pm 0.02$  m and  $\pm 0.01$  m for the position data of the snatch and clean, respectively. The mean differences in peak vertical velocity were less than  $\pm 0.07$  m·s<sup>-1</sup> in the snatch and less than  $\pm 0.01$  m·s<sup>-1</sup> in the clean between software programs. The smoothed and filtered data had mean differences of less than  $\pm 0.02$  m and  $\pm 0.01$  m for the position data of the snatch and clean, respectively. The corresponding mean differences in peak vertical velocity were less than  $\pm 0.03$  m·s<sup>-1</sup> in the snatch and  $\pm 0.04$  m·s<sup>-1</sup> in the clean. However, the smoothness of the position-time curves differed between different interactions of software and

filtering technique (Figure 3). Specifically, the noise in the data obtained using Tracker was successfully removed with either smoothing or filtering, while only filtering successfully removed the noise in the data obtained using Kinovea. Both software programs were found to provide consistent results. When comparing the first and second digitization, there were mean differences in the position data of less than  $\pm 0.01$  m and  $\pm 0.02$  m for snatch and clean, respectively. The corresponding mean differences in peak vertical velocity were less than  $\pm 0.04$  m·s<sup>-1</sup> in the snatch and  $\pm 0.03$  m·s<sup>-1</sup> in the clean.

\*\*\*Figure 3 about here\*\*\*

The lifter demonstrated the characteristic toward-away-toward bar trajectory in the snatch and clean (Figure 4). When videos were processed using Tracker and smoothed with the five point moving arc, net horizontal bar displacement was  $-0.15 \pm 0.04$  m in the snatch and  $-0.13 \pm 0.02$  m in the clean. The peak bar displacement relative to the participant's stature was  $72.3 \pm 1.9\%$  in the snatch and  $58.3 \pm 3.5\%$  in the clean. The difference in vertical position between peak bar height and the height that the bar was received was  $0.27 \pm 0.04$  m and  $0.50 \pm 0.05$  m in the snatch and clean, respectively. Peak bar velocity was  $2.29 \pm 0.08$  m·s<sup>-1</sup> in the snatch and  $2.04 \pm 0.10$  m·s<sup>-1</sup> in the clean (Figure 5). Peak bar velocity in the back squat was  $0.84 \pm 0.08$  m·s<sup>-1</sup>. Additional detail on selected key variables are provided in Tables 2 and 3.

\*\*\*Figure 4 & 5 about here\*\*\*

\*\*\*Table 2 & 3 about here\*\*\*

## **DISCUSSION**

This case study demonstrates the ability to quickly analyze two-dimensional bar kinematics during weightlifting exercises using a low-cost LED-based marker, consumer camera and open source software. Further, this investigation has demonstrated that different software and data processing methods yield nearly identical and consistent results. These methods allow researchers and practitioners to obtain bar kinematic data and assess weightlifting technique without the need for either specialized or expensive hardware and software. The specific bar trajectory a lifter displays influences biomechanical parameters, including joint kinematics and the amount of vertical versus horizontal work performed (7, 15). These parameters may affect the muscles trained and the adaptations elicited. Thus, knowledge of the specific bar trajectory displayed is required to interpret and apply findings in research involving weightlifting exercises. The effect of technique on biomechanics is not unique to weightlifting. In running, foot strike pattern affects lower extremity mechanics and ground reaction forces (20). In vertical jumping, net joint moments differ between proximal-to-distal versus simultaneous sequencing strategies (3). In barbell squats, squat depth affects muscle strength adaptations (1). Therefore, research findings cannot be interpreted correctly without considering the technique employed.

In addition to classifying technique, bar trajectory may be used to objectively evaluate a lifter's performance. The participant in this investigation demonstrated the characteristic towards-away-towards bar trajectory that has previously been noted in world and Olympic calibre weightlifters (7, 17). However, magnitudes of vertical and horizontal bar displacements were greater than in world and Olympic calibre weightlifters (7, 11, 13). For example, peak vertical bar displacement in the snatch and clean were 72.3% and 58.3% of the lifter's stature. The best international lifters have a peak vertical bar displacement of 60% and 50% of their stature, respectively, in the snatch and clean (2, 23). This greater vertical bar displacement resulted in a large drop displacement from peak height to the lowest position in

the receiving phase. Based on this evaluation, we can conclude the participant displayed lifting technique that is consistent with that of high calibre lifters. However, by reducing the magnitudes of vertical and horizontal displacement, the participant's performance could be improved, which may allow heavier loads to be lifted.

The kinematic variables used to evaluate the participant's technique in the snatch and clean were consistent between Tracker and Kinovea and across repeated digitizations. The mean differences in the position data obtained using Tracker and Kinovea were less than  $\pm 0.02$  m. Given that the LED-based marker has approximately this diameter, accuracy could only be improved by reducing the marker size. Thus, similar accuracy can be expected in either Tracker or Kinovea. Smoothing and filtering the raw data provide similar results for the parameters studied. However, based on visual inspection of horizontal and vertical position data, filtering removed noise more effectively from videos that were processed in Kinovea. Smoothing and filtering were equally effective for videos processed in Tracker.

Various methods have been used to obtain bar trajectories in previous studies. 3D optoelectronic motion analysis is commonly used in biomechanics research; these systems are expensive and, thus, not an option for non-biomechanics researchers and non-research settings (10). Most weightlifting technique research has used film or video, and manual digitization (7, 11, 12). Manually digitizing film and video is time consuming (10). Although auto-tracking features are available in several software programs, the bar end is not easy to auto-track accurately. This is because the bar end does not create a sufficient contrast from the surrounding image to be automatically recognized, even when instrumented with a reflective marker or coloured tape. The addition of an LED-based marker enhanced the ability to automatically track the bar end. As a light emitter, the LED-based marker would focus more light on the camera's sensor in contrast to the remainder of objects in the field of view, which are light reflectors.

The LED marker and collar assembly has minimal mass and the weight exerted on the bar is small (0.4 N). For comparison, a single linear position transducer has a cable tension of 1.4 N – 8.2 N (4, 5). To determine vertical and horizontal displacement a pair of linear position transducers are required, further increasing the force exerted on the bar (5). Accelerometers that are marketed for similar purposes are 58 g which would exert 0.6 N. Compared to other instrumentation, an LED-based marker will exert the least force on the bar.

Although the present investigation examined weightlifting, the proposed method could be applied to measure bar kinematics for any barbell exercise, a purpose for which linear position transducers and accelerometers are commonly used (5, 19). An example is provided in the present study of bar velocity during back squat exercise. In addition to exerting less force on the bar, a benefit of this methodology, versus linear position transducers and accelerometers, is that a video record of the lifter is also obtained. A video image of sufficient quality could be used to, either visually or by manually digitizing additional points of interest, evaluate other aspects of the lifter's movement. Further, the video footage can be used to determine movements occurring in other planes, such as bar tilt (frontal plane) or bar rotation (transverse plane) that may invalidate planar assumptions in two-dimensional analysis (8).

In the present study, data were collected on one participant only. However, the ability for software programs to track an LED-based marker is independent of lifting technique, thus, this study presents a proof of concept. In order to auto-track the LED marker, high quality video recordings are paramount. A high quality recording provides a sharp contrast between the LED-marker and its surroundings, while simultaneously providing a good visual record of the lifter (e.g. Figure 2, Panel B.). Further, blurry or pixelated video footage may compromise the accuracy of the auto-tracking, and should be avoided. Video quality is dependent on sensor resolution, lens and zoom, and ability to adjust exposure settings. The camera and lens used in the present investigation allowed the zoom, shutter speed, aperture and ISO settings to

be adjusted. These features allow this camera to record videos with sufficient quality in a large variety of locations and lighting settings. Considering the low cost and high availability of cameras with these features, the methods employed in this study should be available to most researchers, as well as to coaches. Utilizing the methods described would assist coaches in objectively assessing weightlifting technique as exemplified above. Such an assessment can provide detailed information that can help the coaches individualize training to effectively improve their lifters' technique.

In conclusion, using an LED marker provided a sufficient contrast from the surrounding image to obtain two-dimensional bar kinematics using the auto-tracking feature in Tracker and Kinovea. Further, both software packages provided results consistent with each other, and across multiple rounds of data processing. Research involving weightlifting exercises should determine and report the technique used, as study findings may be affected by how the exercises are performed. At minimum, we recommend that participants' bar trajectory should be determined. The current methodology may also be useful to assess bar kinematics in other exercises, having distinct benefits in comparison to commonly used instruments such as linear position transducers and accelerometers.

## **PRACTICAL APPLICATIONS**

This case study proposes a method to examine weightlifting technique using an LED-based marker, consumer camera and open source software. Considering the accessibility and low cost of this method, it is feasible for coaches to use this method to objectively evaluate the technique of athletes performing weightlifting exercises. For example, an individual who does not have the characteristic towards-away-towards trajectory may benefit by improving their technique to exhibit this trajectory (16, 22). An individual who elevates the bar to an unnecessary height may benefit by focussing on the transition between second pull and squat

under phases (6). Moreover, kinematic parameters could be examined periodically, to evaluate training program effectiveness. Ultimately, objective measures, such as bar kinematics, of how an exercise is performed provides information that may be used to enhance training efficacy.



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Figure 1. The LED marker and collar assembly placed on the right bar end.

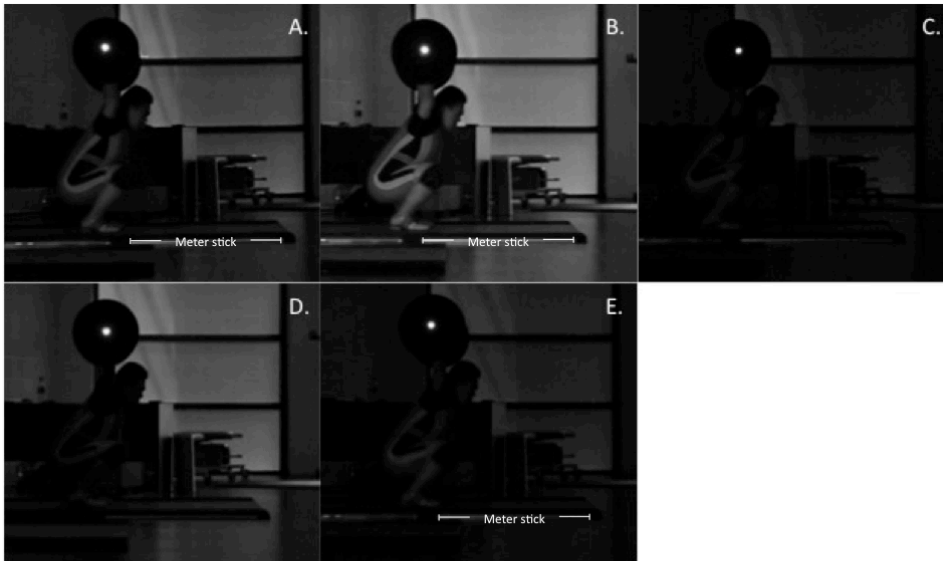


Figure 2. Individual frames from set 1 (A.), 2 (B.), 3 (C.), 4 (D.) and 5 (E.) of the snatch, captured with various camera settings (Table 1). For videos with sufficient quality to view, the reference length meter stick is highlighted (A., B. and E.).

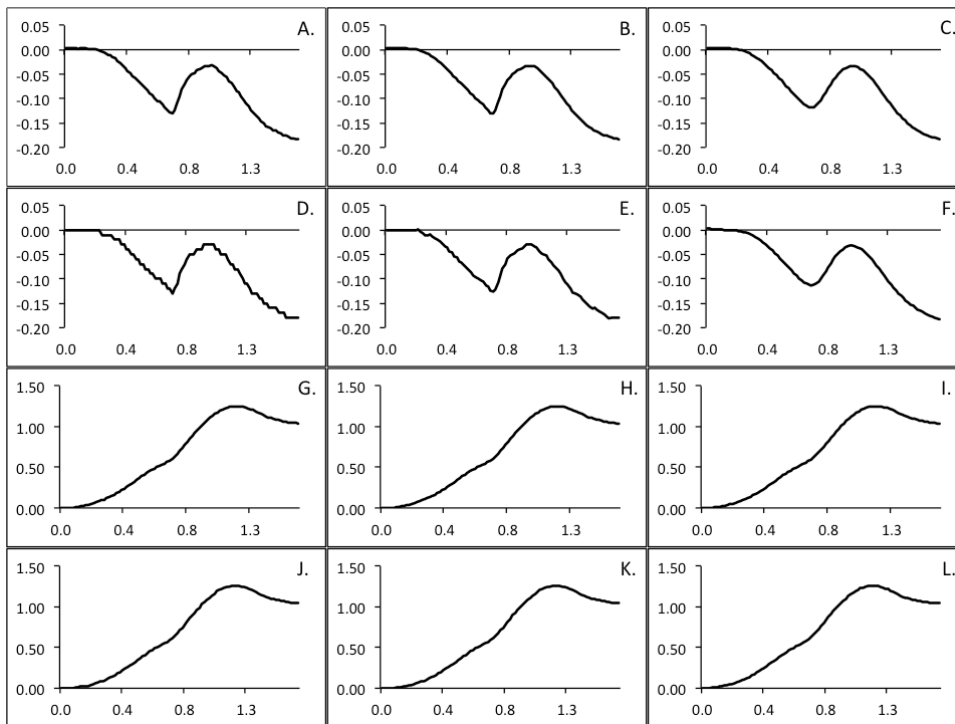


Figure 3. Raw (A., D., G. and J.), smoothed (B., E., H. and K.) and filtered (C., F., I. and L.) horizontal (A. through F.) and vertical (G. through L.) position coordinates from a representative snatch lift. Data obtained from Tracker are shown in panels A. through C. and G. through I. Data obtained in Kinovea are shown in panels D. through F. and J. through L. The horizontal axes indicate time (s) and the vertical axes indicate displacement (m).

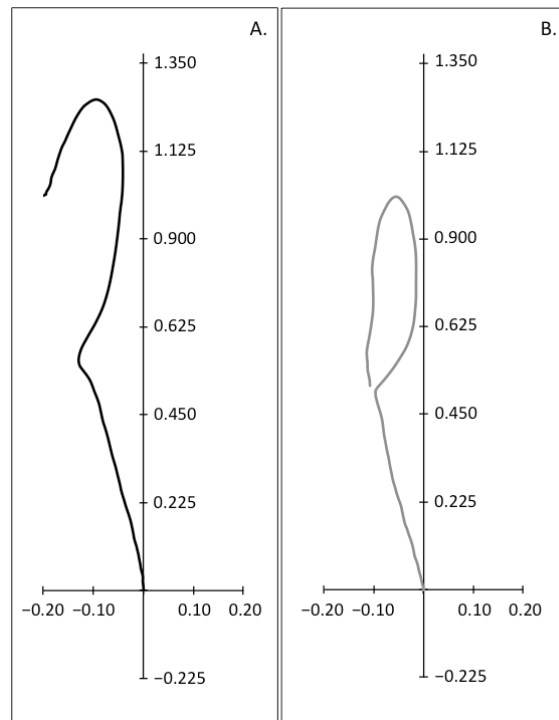


Figure 4. A representative bar trajectory of the participant's snatch (A.) and clean (B.). Positive values indicate superior and anterior with respect to the bar's position at lift-off.



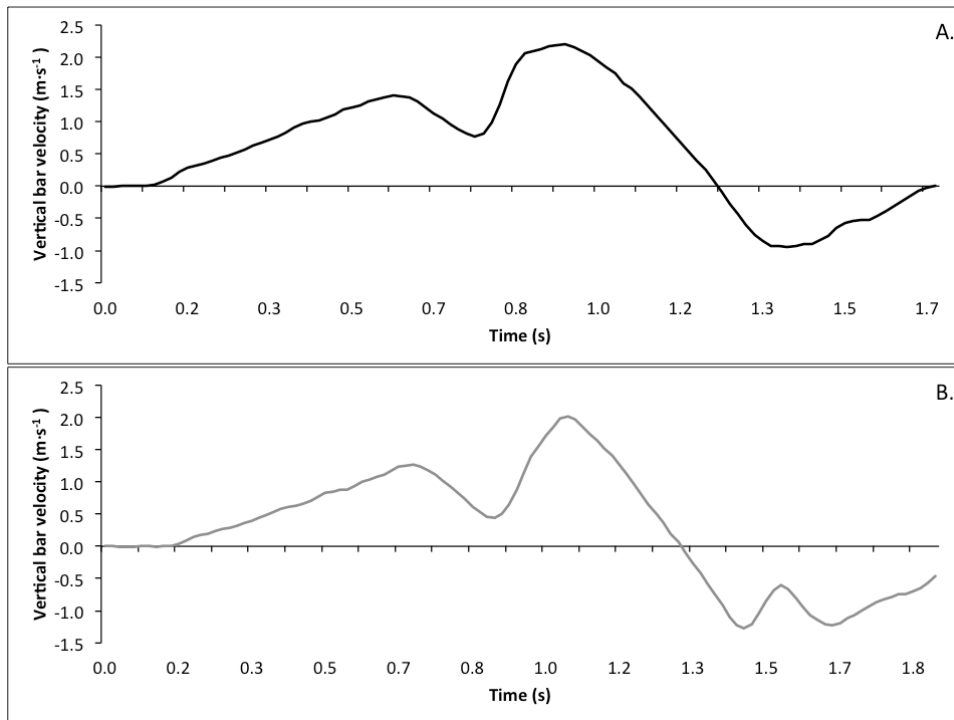


Figure 5. The vertical bar velocity of a representative snatch (A.) and clean (B.).

Table 1. Barbell load, repetitions, shutter speed and ISO setting used for the individual sets of the snatches and cleans.

<i>Exercise</i>	<i>Set</i>	<i>Barbell Load</i>	<i>Repetitions</i>	<i>Shutter Speed</i>	<i>ISO</i>
Snatch	1	50 kg	3	1/500	800
Snatch	2	50 kg	3	1/250	800
Snatch	3	50 kg	3	1/1250	800
Snatch	4	50 kg	3	1/100	100
Snatch	5	70 kg	2	1/500	400
Snatch	6	70 kg	2	1/500	800
Snatch	7	90 kg	1	1/500	400
Snatch	8	100 kg	1	1/500	400
Snatch	9	100 kg	1	1/500	400
Snatch	10	100 kg	1	1/500	400
Clean	1	50 kg	2	1/500	400
Clean	2	50 kg	2	1/500	400
Clean	3	90 kg	1	1/500	400
Clean	4	110 kg	1	1/500	400
Clean	5	120 kg	1	1/500	400
Clean	6	120 kg	1	1/500	400
Clean	7	120 kg	1	1/500	400
Back Squat	1	120 kg	2	1/500	400
Back Squat	2	140 kg	1	1/500	400
Back squat	3	140 kg	1	1/500	400

Table 2. Comparisons of the two software packages, smoothing and filtering, and intra-rater consistency for the snatch lifts. Mean and standard deviation is presented.

		<b>Snatch</b>					
		<i>T1 5MA</i>	<i>T1 FD</i>	<i>T2 5MA</i>	<i>K1 5MA</i>	<i>K1 FD</i>	<i>K2 FD</i>
$s_{Y_{peak}}$	(m)	1.29 ± 0.03	1.29 ± 0.03	1.28 ± 0.03	1.31 ± 0.04	1.31 ± 0.04	1.30 ± 0.04
$s_{Y_{drop}}$	(m)	0.27 ± 0.04	0.27 ± 0.04	0.27 ± 0.04	0.28 ± 0.04	0.28 ± 0.04	0.27 ± 0.04
$v_{Y_{peak}}$	(m·s <sup>-1</sup> )	2.29 ± 0.08	2.29 ± 0.08	2.28 ± 0.08	2.36 ± 0.10	2.34 ± 0.10	2.31 ± 0.09
$s_{X_1}$	(m)	-0.12 ± 0.01	-0.11 ± 0.01	-0.12 ± 0.01	-0.12 ± 0.02	-0.11 ± 0.02	-0.11 ± 0.01
$s_{X_2}$	(m)	0.13 ± 0.03	0.12 ± 0.03	0.13 ± 0.03	0.14 ± 0.03	0.12 ± 0.03	0.12 ± 0.03
$s_{X_{loop}}$	(m)	-0.16 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02
$s_{X_{net}}$	(m)	-0.15 ± 0.04	-0.15 ± 0.04	-0.15 ± 0.04	-0.15 ± 0.04	-0.15 ± 0.04	-0.15 ± 0.04

$s_{Y_{peak}}$  = peak vertical bar displacement,  $s_{Y_{drop}}$  = drop in bar height from  $s_{Y_{peak}}$  to the bottom position of the receiving phase,  $v_{Y_{peak}}$  = peak vertical bar velocity,  $s_{X_1}$  = horizontal bar displacement during the first pull,  $s_{X_2}$  = horizontal bar displacement during the transition phase and second pull,  $s_{X_{loop}}$  = horizontal bar displacement during the turnover and receiving phase,  $s_{X_{net}}$  = net horizontal bar displacement, T1 = digitization 1, Tracker, T2 = digitization 2, Tracker, K1 = digitization 1, Kinovea, K2 = digitization 2, Kinovea, 5MA = Five-point moving arc, FD = Filtered data.

Table 3. Comparisons of the two software packages, smoothing and filtering, and intra-rater consistency for the clean lifts. Mean and standard deviation is presented.

		<b>Clean</b>					
		<i>T1 5MA</i>	<i>T1 FD</i>	<i>T2 5MA</i>	<i>K1 5MA</i>	<i>K1 FD</i>	<i>K2 FD</i>
$s_{Y_{peak}}$	(m)	1.04 ± 0.06	1.04 ± 0.06	1.02 ± 0.04	1.03 ± 0.04	1.03 ± 0.04	1.04 ± 0.05
$s_{Y_{drop}}$	(m)	0.50 ± 0.05	0.50 ± 0.05	0.50 ± 0.04	0.50 ± 0.04	0.50 ± 0.04	0.51 ± 0.04
$v_{Y_{peak}}$	(m·s <sup>-1</sup> )	2.04 ± 0.10	2.02 ± 0.12	2.01 ± 0.06	2.05 ± 0.08	2.01 ± 0.07	2.03 ± 0.09
$s_{X_1}$	(m)	-0.10 ± 0.01	-0.09 ± 0.01	-0.10 ± 0.01	-0.10 ± 0.01	-0.09 ± 0.02	-0.09 ± 0.01
$s_{X_2}$	(m)	0.08 ± 0.01	0.07 ± 0.01	0.08 ± 0.01	0.08 ± 0.01	0.08 ± 0.02	0.07 ± 0.01
$s_{X_{loop}}$	(m)	-0.11 ± 0.01	-0.11 ± 0.01	-0.11 ± 0.01	-0.11 ± 0.01	-0.11 ± 0.01	-0.11 ± 0.01
$s_{X_{net}}$	(m)	-0.13 ± 0.02	-0.13 ± 0.01	-0.13 ± 0.02	-0.13 ± 0.02	-0.13 ± 0.01	-0.13 ± 0.02

$s_{Y_{peak}}$  = peak vertical bar displacement,  $s_{Y_{drop}}$  = drop in bar height from  $s_{Y_{peak}}$  to the bottom position of the receiving phase,  $v_{Y_{peak}}$  = peak vertical bar velocity,  $s_{X_1}$  = horizontal bar displacement during the first pull,  $s_{X_2}$  = horizontal bar displacement during the transition phase and second pull,  $s_{X_{loop}}$  = horizontal bar displacement during the turnover and receiving phase,  $s_{X_{net}}$  = net horizontal bar displacement, T1 = digitization 1, Tracker, T2 = digitization 2, Tracker, K1 = digitization 1, Kinovea, K2 = digitization 2, Kinovea, 5MA = Five-point moving arc, FD = Filtered data.

## Notification of Approval

Date: September 16, 2015  
Study ID: Pro00057564  
Principal Investigator: [Torstein Eriksen Daehlin](#)  
Study Supervisor: [Loren Chiu](#)  
Study Title: Internal and External Kinetics of Three Variations of the Clean Exercise  
Approval Expiry Date: Thursday, September 15, 2016

Approved Consent Form:	Approval Date 9/16/2015 9/16/2015	Approved Document <a href="#">Informed Consent Information letter</a>
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Thank you for submitting the above study to the Research Ethics Board 2 . Your application has been reviewed and approved on behalf of the committee.

A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

Approval by the Research Ethics Board does not encompass authorization to access the staff, students, facilities or resources of local institutions for the purposes of the research.

Sincerely,

Stanley Varnhagen, PhD  
Chair, Research Ethics Board 2

*Note: This correspondence includes an electronic signature (validation and approval via an online system).*



## INFORMATION LETTER

### STUDY TITLE: INTERNAL AND EXTERNAL KINETICS OF THREE VARIATIONS OF THE CLEAN EXERCISE

#### Research Investigator:

Torstein E. Daehlin, BS,  
Masters student  
Department of Physical Performance  
Norwegian School of Sports Sciences  
Mobile Phone: 780-710-3474

#### Study Team:

Loren Z. F. Chiu, PhD, CSCS  
Associate Professor  
Neuromusculoskeletal Mechanics Research Program  
Faculty of Physical Education and Recreation  
University of Alberta  
Office Phone: 780-248-1263

#### Background

- You are being asked to participate in this study because you have experience performing the clean exercise.
- This research will provide information about the optimal method to perform the clean exercise.

#### Purpose

1. The first purpose of this research study is to determine which method of performing the clean exercise requires the least mechanical effort.
2. The second purpose of this research study is to determine how hard different muscles work when different methods are used to perform the clean exercise.

#### Study Procedures

- Your participation will require 2 visits to the Sports Biomechanics Laboratory. Each visit will take approximately 1 hour.
- In the first session we will determine the most weight you can lift for one repetition in the clean exercise while recorded by a digital video camera.
- In the first session you will practice the power clean, maximal effort clean and optimal height clean.
- In the second session, you will be recorded using a 3D motion capture system while you perform these three variations of the clean.
  - Reflective markers will be put on your body for motion capture cameras to record.
  - You will stand on two force platforms that will measure how hard your legs push towards the ground when you perform the cleans.
- For each variation, you will perform 4 sets of 1 repetition using 80% of the maximum weight you can lift for one repetition.

#### Benefits

- You will receive feedback about how you perform the clean exercise.
- We hope that the information from this study will help us understand which method of performing cleans is most efficient.



## INFORMATION LETTER

### STUDY TITLE: INTERNAL AND EXTERNAL KINETICS OF THREE VARIATIONS OF THE CLEAN EXERCISE

- The information in this study may help us to understand how muscles are involved in performing clean exercise.

#### Risk

- The risks of participating in this study are the same as the risks involved in performing clean exercise for training or competition.
- There is the potential to strain the muscles of the shoulder, back, thigh and calf.
- These risks should be minimal as you have experience performing clean exercise.

#### Voluntary Participation

- You are under no obligation to participate in this study. Your participation is completely voluntary.
- Even if you agree to be in the study, you can change your mind and withdraw. You can withdraw by speaking to any member of the study team at any time prior to completing the second session. If you withdraw before data collection is finished, your data will be destroyed.

#### Confidentiality & Anonymity

- We intend to present this research at conferences and publish this research in journals.
- All data collected will be kept confidential and only members of the study team will have access to the data.
- Your identifying information will not be associated with the data.
- Your face may be captured on the digital videos
  - Videos will be used for research purposes
  - Videos may be used for presentations/publications and teaching purposes, if you provide consent
- All data will be stored securely, including in locked filing cabinets and password protected computers.
- The data we collect in this study will be retained for a minimum of five years.

#### Further Information

- If you have any further questions regarding this study, please do not hesitate to contact Dr. Loren Chiu at (780) 248-1263.
- The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615.



**INFORMED CONSENT FORM**

**STUDY TITLE: INTERNAL AND EXTERNAL KINETICS OF THREE VARIATIONS OF THE CLEAN EXERCISE**

Research Investigator: Torstein E. Daehlin, Department of Physical Performance, The Norwegian School of Sports Sciences, 780-710-3474

**Part 2 (to be completed by the research participant)**

Do you understand that you have been asked to be in a research study?	Yes	No
Have you received and read a copy of the attached Information Sheet	Yes	No
Do you understand the benefits and risks involved in taking part in this research study?	Yes	No
Have you had an opportunity to ask questions and discuss this study?	Yes	No
Do you understand that you are free to refuse to participate, or to withdraw from the study at any time, without consequence, and that your information will be withdrawn at your request?	Yes	No
Has the issue of confidentiality been explained to you? Do you understand who will have access to your information?	Yes	No
I consent to the collection and use of video recordings for research purposes	Yes	No
I consent to the use of the video recordings for publication/presentation purposes	Yes	No
I consent to the use of the video recordings for teaching purposes	Yes	No

This study was explained to me by: \_\_\_\_\_

I agree to take part in this study:

\_\_\_\_\_  
Signature of Research Participant

\_\_\_\_\_  
Date

\_\_\_\_\_  
Witness

\_\_\_\_\_  
Printed Name

\_\_\_\_\_  
Printed Name

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

\_\_\_\_\_  
Signature of Investigator or Designee

\_\_\_\_\_  
Date

**The information sheet must be attached to this consent form and a copy of both forms given to the participant.**

Document Version Date: August 29, 2015





# Olympic Weightlifting Study

We are studying the optimal methods of performing the clean exercise.

Participants will receive feedback on how they perform the clean exercise from a certified weightlifting coach.

Men and women may be eligible if they:

- Are between 18 and 50 years old
- Have at least 1 year experience with performing the clean exercise

For more information:

**CONTACT:** Torstein Eriksen Daehlin

**EMAIL:** [eriksend@ualberta.ca](mailto:eriksend@ualberta.ca)

**TELEPHONE:** 780-710-3474

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