Power output and loads on the lumbar vertebrae during a power clean

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Power Output and Loads on the Lumbar Vertebrae during a Power Clean

by

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ABSTRACT

The purpose of the present study was to compare the peak resultant torque, shear, and compressive forces acting at the L3/L4 junction of the lumbar vertebrae and the peak power output during 40% one repetition maximum (1RM) and 80% 1RM attempts of the power clean. It was hypothesized that performance of a power clean at 80% 1RM will result in greater peak resultant compressive force, torque and shear force at the L3/L4 junction of the lumbar spine than that of a 40% 1RM attempt. Power cleans at 80% 1RM will also result in higher maximum instantaneous power outputs than that of the 40% attempts. The power clean attempts for each participant were performed on a force plate and video recorded. Kinetic data from the force plate and kinematic data derived from the videorecords were used in an inverse dynamic analysis to determine the peak resultant torque, shear force, and compressive force at the L3/L4 junction. Peak instantaneous power was calculated using data from the force platform. Statistical analysis revealed that the means for all four dependent variables were significantly greater during attempts at 80% 1RM than 40% 1RM. It was also found that from 40% to 80% attempts, peak torque increased by 52%, peak shear force increased by 64%, peak compressive force increased by 49% and power increased by 22%. Given the smaller percent increase in power relative to the forces experienced it is questionable whether or not increasing loads to 80% is worth the increase in torque and forces sustained at the L3/L4 junction.
ACKNOWLEDGEMENTS

First and foremost I would like to thank my Committee Chair, Dr. Peter McGinnis for the countless hours he has worked during the thesis process and the guidance he has provided over the years, this project would not have been possible without him. I would also like to thank Dr. Jeff Bauer and Dr. John Foley for their generous guidance and assistance. Lastly, I would like to thank my mother, Susan Keleher, for her constant support of all varieties, without her none of this would have been possible.
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CHAPTER 1

INTRODUCTION

In athletic activities, the athlete must produce a substantial amount of power to be successful (Luebbers et al., 2003; McNeely, 2007; Frounfelter, 2009). Power is defined as the product of force and velocity, in other words, the ability to create force at a relatively high velocity (Seigel, Gilders, Staron, & Hagerman, 2002; McBride, Triplett-McBride, Davie, & Newton, 1999). There are several ways of training to improve power including weightlifting, power-lifting, and plyometrics, but all have injury risks specific to their training type. One exercise that has been shown to produce higher power outputs and improve athletic power is the power clean (Haff & Potteiger, 2001, Kawamori & Haff, 2004). The power clean involves lifting a weight off of the floor, accelerating it upward in a straight line, and catching it on the chest and shoulders. The importance of this exercise is the act of triple extension. Triple extension is the extension of the knee, hip, and ankle joints during an explosive activity, such as a vertical jump (Frounfelter, 2009). While a properly executed power clean can benefit the velocity of force production, some people are concerned that the lift puts athletes at a risk of injury, especially injury to the lumbar spine. Bruce-Low and Smith (2007) believe the execution of explosive exercises should be reserved for those who train to lift weights rather than those who train for another sport to increase power because these lifts do not positively transfer to outside sport skills and pose a greater risk of injury. Some previous studies have examined the effects of lifting on the mechanical stress placed on the lumbar spine.
but few have involved the use of various percentages of maximal lifting capability performed by their participants.

**Statement of the Problem**

The purpose of the present study was to compare the peak resultant torque, shear, and compressive forces acting at the L3/L4 junction of the lumbar vertebrae and the peak power output during 40% one repetition maximum (1RM) and 80% 1RM attempts of the power clean.

**Significance of the Study**

While explosive lifts such as the power clean have been associated with an increased power and performance of many athletic populations, they also increase the risk of injury for the population in training. Since explosive lifts are intended to be performed at maximal velocity, the fitness professional should consider the method in which explosive lifts are performed and the magnitude of the loads lifted to minimize the risk of injury. Kawamori and Haff (2004) suggest that using a training load that results in the highest mechanical power output will benefit the athlete’s training goals but this conclusion is likely too broad because it does not account for the risks of injury associated with performing those heavy loads. It is important to note as well that an optimal load that maximizes power output has only been speculated, not found (Chiu, 2010). Utilizing a load in which the mechanical power output is at its greatest could potentially increase the risk of injury because of the stress placed on different portions of the body, most notably the lumbar spine. Hall (1985) examined the performance of the clean and jerk at various training loads. The mean compressive force, mean shear force, and maximum myoelectric activity in the lumbar spine were all greater at heavier loads.
The greater forces on the lumbar spine during heavier resistance may suggest a greater risk of injury in the region than that of lower resistances. Knowledge of the load imposed on the lumbar spine during cleans with different loads may be useful to coaches, fitness professionals, and medical professionals in deciding whether to prescribe this exercise to their clients/patients and also in determining the appropriate loads for this exercise based upon the stress placed on the lumbar spine. It is also important to consider the effect that an increased load has on the power output. Once this effect is determined and understood, professionals will be able to take a second look at the loads they are prescribing to their clients or athletes and decide on the safest, yet most effective method of training.

**Hypothesis**

Performance of a power clean at 80% 1RM will result in greater peak resultant compressive force, torque and shear force at the L3/L4 junction of the lumbar spine than that of a 40% 1RM attempt. Power cleans at 80% 1RM will also result in higher maximum instantaneous power outputs than that of the 40% attempts.

**Delimitations**

The delimitations of this study were:

1. The participants were nine male collegiate track and field athletes who had previous training with the power clean.
2. The participants included only those who had at least two years of experience with the power clean.
3. Individual 40% and 80% 1RM resistances were determined and used for each participant.
4. Torque, compressive forces, and shear forces at the L3/L4 junction were 
examined.

5. The analysis was based on a two-dimensional model only.

6. Only one trial of each participant was analyzed.

Limitations

The limitations of this study were:

1. The accuracy of position data for some markers was limited due to the 
obstruction of markers in the camera view during parts of the lift.

2. Maximum effort may not have been put forth by the participants.

3. The calculation of power output was based on the assumption that the athlete 
and barbell were stationary at the start of the power clean, i.e., the initial 
velocity of the athlete and barbell were zero. Slight movement of the athlete 
and barbell may have affected the power calculation, but the size of the error 
was considered to be insignificant when compared to the differences in peak 
power output.

Assumptions

1. Each participant was assumed to execute each lift with maximal effort.

2. The movements were assumed to occur primarily in two-dimensions in the 
sagittal plane.

Operational Definition of Terms

1. Power Clean: a dynamic lifting exercise performed to increase the power 
capabilities of the performer. Involves the performance of the triple extension to
accelerate a weighted barbell upward from the floor in a vertical path and catch it upon the chest and shoulders.

2. **Power**: the product of force and velocity. \( P = Fv \)

3. **Pronated grip**: a gripping technique where the bar is held with all fingers wrapped around the bar and the palms face downward.

4. **Hook grip**: similar to the pronated grip in that the fingers and thumbs are wrapped around the bar but the grip is enhanced by placing the thumbs underneath the other four fingers.

5. **Lumbar spine**: the five vertebrae, L1-L5, in the lower back below the thoracic vertebrae and above the sacrum.

6. **L3/L4**: region of the lumbar spine between the 3rd and 4th lumbar vertebrae. The junction of the L3/L4 represents the transverse plane that passes through the intervertebral disc between them. Calculations to determine the resultant compressive force, shear force, and torque were done at this plane.

7. **1RM**: One repetition maximum. The amount of resistance that can be performed only one time through maximal effort.

8. **%1RM**: a given percentage of a one repetition maximum.

9. **Spondylolysis**: a unilateral or bilateral stress fracture in the lumbar vertebrae and results in moderate to severe lower back pain.

10. **Compressive force**: pushing force whose direction and point of application would tend to shorten or squeeze an object along the dimension coinciding with the line of action of the force (McGinnis, 2005).
11. Shear Force: force or stress acting parallel to the analysis plane or perpendicular to the long axis of the object; shear stress tends to slide molecules past each other and skew the object (McGinnis, 2005).

12. Torque: the turning effect created by a force about an axis; force times moment arm; (McGinnis, 2005).
CHAPTER 2
REVIEW OF LITERATURE

The purpose of this study was to compare the peak resultant torque, shear, and compressive forces acting at the L3/L4 junction of the lumbar vertebrae and the peak power output during 40% 1RM and 80% 1RM attempts of the power clean. The following reviews of the literature included those related to the technique of the power clean, weight training to increase power in athletics, and the risks associated with power training and explosive lifts. Power is a major contributor to performance improvement and success in many sport activities today. Power is the ability to generate significant forces at high velocities and can be improved using many different exercise modes.

Technique of the Power Clean

The power clean is a technical and dynamic exercise that requires the participant to lift and accelerate a barbell from the floor in an explosive manner, focusing on the triple extension of the ankle, knee, and hip joints and finishing by catching it upon the chest and shoulders (Judge, Wang, Craig, & Bellar, 2012). The desired training adaptation of this exercise is to improve explosive strength and power which are both key components of success in athletics (Frounfelter, 2009; Judge et al., 2012). The power clean requires great attention to detail to ensure the safety and effectiveness of training (Garhammer, 1984; Duba, Kraemer, & Martin, 2007; Souza & Shimada, 2002). According to Graham (2000), the muscles that are primarily used to execute the lift include the gluteus maximus, hamstrings, quadriceps, soleus, gastrocnemius, trapezius, and deltoids. Others suggest that it involves the majority of the body’s major muscle
groups which is a reasonable assumption considering the coordination and balance that it requires (Garhammer, 1984). The power clean has been categorized as an Olympic style lift, where the primary goal of the exercise is to enhance the ability of an athlete/weightlifter to produce force at a rapid rate. According to Souza and Shimada (2002), the power clean has 4 phases, the first pull, unweighted, second pull, and catch phase but these phases may also be described as the first pull or ascent, the transition or scoop, the second pull or power phase, and the catch (Graham, 2000; Garhammer, 1984; Judge et al., 2012).

Before elaborating on each phase it is important to define the starting position as described by Graham (2000). The athlete should be using a standard Olympic bar with an even load on each side held in place by collars. The feet of the athlete should be placed firmly on the platform approximately shoulder width apart. The athlete proceeds by squatting and grasping the barbell with locked arms placed outside of the knees. The grip should be pronated or palms down, either hook or closed, approximately shoulder width apart as well. At this point the bar should be almost brushing the shins and directly over the centers of the feet and below the knees. It is very important that the athlete keep their back flat or slightly arched. Keeping their eyes forward or slightly upward will assist the athlete in keeping their back flat, shoulder blades pinched closely together, and their chest pushed up and out (Graham, 2000). These are all key components to safety in performance of the power clean.

The actions of all of the components of the power clean have also been described in detail by Graham (2000) and should be performed as follows. During the first pull the bar is to be accelerated directly upward through powerful extension of the hip and knee
joints. During the first pull of the clean it is important that the athlete maintain the original posture of the torso and also of the head. The shoulders should still be directly over or a little in front of the barbell itself and the barbell should remain close to the shins throughout the initial movement. During the first pull, the elbows should stay maximally extended. The transition phase, or scoop, is initiated immediately after the first pull and is noted by the athlete allowing slightly more bend at the knees and pushing the hips forward so that the bar is touching at approximately the mid-thigh. The orientation of the back, torso, head, and elbows should remain the same throughout the transition phase. After the transition phase, the athlete begins the second pull, or power phase, by explosively performing triple extension of the ankle, knee, and hip joints. This phase however, is noted by adding a strong and powerful shrug of the shoulders upward. This will result in a rapid acceleration of the bar in the upward direction and the elbows start to flex and the torso gains an upright position. Flexion of the elbows will allow the athlete to pull their body under the bar. The final phase of the power clean, the catch, is performed immediately during the end of the second phase where the athlete’s body is now underneath the bar at its maximum height. During the catch the athlete should pull their body underneath the bar and catch it upon their anterior deltoids, chest, and clavicles. The body positioning at this point should be similar to the top half of a front squat. Following the catch the athlete should be balanced in this front squat position and once again extend the hips and knees to stand up into an upright position, maintaining a flat back with feet facing forward planted firmly underneath the overall center of gravity. The barbell should be returned to the floor in a controlled manner. First, by flexing the hips and lowering it to the upper thigh area, keeping it close to the body to avoid
unwanted torque that could result in potential injury, and then in much the same manner, lowering it to the floor to complete the lift (Graham, 2000).

**Training Power in Athletics**

There are various methods that are used to improve lower body strength and power (Bauer, Thayer, & Baras, 1990). Perhaps the most popular are standard heavy weight-lifting, plyometric training, and Olympic style power-lifting. There have been numerous studies that examine the training effects of these methods. Lyttle, Wilson, and Ostrowski (1996) performed a study that compared the performance effects of different training groups, including a plyometrics/heavy weight-lifting group and a maximal power training group. Results of the study showed significant increases in performance of many upper and lower body activities but no significant differences between training groups, suggesting that both methods were similarly effective in increasing performance. These results were similar to that of Bauer et al. (1990) who also compared the effectiveness of several different training modalities over the course of a 10 week training period that included a plyometrics group and a combination of free weights and plyometrics group. Bauer et al. found no significant differences between training groups but within group statistics showed significant improvements in tests such as the vertical jump and peak torque in the quadriceps for each training modality. Plyometric exercises have been widely accepted as a training method to improve physical power. McNeely (2007) even suggests that plyometric training is superior to any other mode of power training because of the ability to concentrate on sport-specific movements and speeds. While McNeely insists that plyometrics are the superior form of power training because of their contribution to the velocity portion of the force/velocity curve he also suggests that
standard weight training allows the body to undergo the neurological and physiological adaptations to gain strength. It seems as though weight training contributes to the force portion of the force velocity curve while plyometrics contribute to the velocity portion, resulting in each training mode having a comparable impact on the resulting power output (McNeely).

**Risks of Injury Associated with Power Training**

Explosive lifts such as the power clean have been utilized by coaches and athletes with the hopes of increasing the rate of force production or power output. However, the risk factors associated with this type of exercise have recently become the focus of a good deal of research attention. Hall (1985) examined the effects of various lifting speeds during the snatch on the forces and torque in the lumbar region of the spine. It has been found that the lumbar region is the area in which most injuries or sites of chronic pain have shown to be relatively frequent. Loads of 40, 60, and 80% were used and lifts were performed at three different target times of 1.5, 3, and 7 seconds. It was found that torque, shear, and compressive forces were greatest during the fast attempts when acceleration of the barbell was the highest. The maximum EMG activity and compressive forces were significantly lower during 40% attempts than for the 60 and 80% attempts while the shear forces were significantly higher at 80%. This may suggest that lower percentages of 1RM could reduce the magnitudes of these forces and in turn prevent injuries to the lumbar region of the spine assuming that lifting speed remains relatively similar since it contributes to these forces substantially. Risser, Risser, and Preston (1990) examined the weight-training routines of high school football players and found that the most frequent site of injury occurred in the lower back at 48.2% of the
sample size. Also interesting was the finding that 60% of those who took part in explosive lifting had incidences of injury in the lower back as opposed to only 14.3% in those who did not perform this type of lifting. In two studies examining the relevance of spondylolysis in different groups of athletes showed that repetitive hyperextension is the root cause of lower back pain associated with this illness (Carlson, 2007; Rossi & Dragoni, 1990). Spondylolysis is defined as a unilateral or bilateral stress fracture in the lumbar spine and results in moderate to severe lower back pain, especially during the relative sporting activity (Carlson, 2007). Rossi and Dragoni (1990) examined clinical records and images from over 3000 competitive athletes and found that 390 of the athletes had spondylolysis and 22 of the 97 weight-lifters (22.7%) in the study had spondylolysis. When compared to the typical non-athletic adult population, having approximately 4-6% incidences of spondylolysis, 22.7% is very high. In a similar study regarding heavyweight lifting, Carlson (2007) showed that the incidence of spondylolysis was between 15-36%. Kotani, Ichikawa, Wakabayashi, Yoshii, and Koshimune (1971) had similar findings among weight-lifters in their study where 30.7% (8 out of 26 subjects) had spondylolysis. Granhed and Morelli (1988) examined the prevalence of lower back pain among a sample of retired wrestlers and weightlifters. Although the data were collected 20 years after retirement, this study portrayed possible risk outcomes for the lower back in those who took part in competitive athletics for extensive periods of time during their youth. The findings of this study showed that chronic lower back pain was prevalent in approximately 23% of the weight-lifting sample and 59% of the wrestling sample (Granhed & Morelli, 1988).
CHAPTER 3

METHODOLOGY

The purpose of this study was to compare the peak resultant joint torque, peak resultant joint compressive force, and peak resultant joint shear force at the transverse plane between the third and fourth lumbar vertebrae (L3/L4) for power cleans at 40% 1RM and 80% 1RM and to determine the respective maximum instantaneous power outputs.

Participants

The subjects were nine well-trained male collegiate track and field athletes ranging in age from 18 to 24 years who had at least two years of experience performing the power clean as part of their sport specific training regimen. The subjects were members of an NCAA Division III varsity team (see table 1).

Table 1. Participant Information

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age (yrs.)</th>
<th>Experience (yrs.)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Estimated 1RM (kg)</th>
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**Instrumentation**

A mini-DV video camera (JVC model #GR-DF550U) was used to record a sagittal view of each subject’s lifts. The camera was rotated 90 degrees to maximize the field of view vertically. The optical axis of the camera lens was set perpendicular to the sagittal plane. The height of the lens was 1.01 m above the floor and the camera was placed 5.55 m directly to the side of the force platform where the lifts were performed. The camera recorded 60 fields/second with a shutter speed of 1/250th second. A 300 watt lamp was placed directly beneath the video camera facing the direction of the force platform. The video signal from the camera was input to a Peak Motus event and video control unit (E&VCU). The video signal output from the E&VCU, which included the original video signal overlaid with a synchronizing signal to allow synchronizing of the video records with the force platform data, was recorded by a SONY mini-DV recorder (SONY DV1000). A force platform (Bertec #K00606, type 4060-10, Columbus, OH, 40x60cm) was used to measure the ground reaction forces during each lift.

**Experimental Protocol**

All procedures were reviewed and approved by the SUNY Cortland Institutional Review Board prior to data collection (see appendix D). The risks and benefits of participation were thoroughly explained to the subjects. Each subject signed a statement of informed consent (see appendix A).

Prior to testing, each subject was asked to fill out a Physical Activity Readiness Questionnaire (PAR-Q, ACSM) and a participant information questionnaire (PIQ) (see appendix B and C). Information such as height, weight, gender, age, and estimated maximum load for a power clean were recorded on the PIQ. Based on the load recorded
in the PIQ, a one repetition maximum (1RM) for each participant was estimated using the
National Strength and Conditioning Association’s 1RM calculator (NSCA, n.d.) and 40% and 80% of this load was used during the experimental protocol. The loads of 40% and 80% were similar to those used in the study by Hall (1985).

On testing day, participants entered the laboratory at one-hour intervals. The procedures were reviewed with the participant, including information about the lift and loads to be lifted. The participant was asked if he was injured in any way that could hinder his performance and he was also asked if he still agreed to participate in the study. Each participant then performed a 5 minute warm-up on a stationary bike using a self-selected intensity. After this warm-up, 2 cm diameter spherical reflective markers were placed on the left side of the participant at the following locations: the tip of the longest toe (TTIP), the heel (HEEL), the ankle joint center (AJC), the knee joint center (KJC), the hip joint center (HJC), the shoulder joint center (SJC), and the end of the weighted barbell (WB). The participant then performed a warm-up set of 5 repetitions of the power clean using a load of 30% 1RM. After the warm-up set the participant was given three to five minutes of rest in preparation for the first experimental lift of 40% 1RM. While the subject rested, the barbell was loaded with 5 and 10 pound plates equal to the participant’s 40% 1RM.

After rest the rest period, the participant was asked to stand with both feet on the force platform. A sign placed behind the subject and in the video camera’s field of view indicated the subject’s identification number (ID#), load, and attempt number. The video camera and the 300W lamps were turned on. The data collection setup is shown in Figure 1. The record button in the Acquire window of the Peak MOTUS computer software was
activated, the mini-DV camera and the mini-DV recorder began recording, and a “GO” command to the participant was given. The participant then initiated the power clean when he was ready. When the lift was initiated, the trigger of the E&VCU was pushed to begin recording the ground reaction forces by the Peak MOTUS system. The Peak Motus software was set to record the force data for 2 seconds before the trigger and 3 seconds after the trigger for a total recording of 5 seconds per attempt. The analog output from the force platform was amplified and converted to digital data and recorded on the computer hard drive by the Peak Motus software.

After the 40% 1RM attempt was performed, the participant was given a 3-5 minute rest period. After each trial, video recording stopped, the lights were shut off, and the force data were checked and saved to the computer hard drive under a file name associated with the subject’s identification number. When the rest period was concluded the same protocol was followed for the 80% 1RM attempt. The data collection setup is shown in Figure 1.

Following each subject’s data collection session, reflective markers were placed on the front and rear edges of the force platform and video-recorded. These markers were used to determine the location of the application of force on the force platform relative to the coordinate system of the digitized video. A one-meter long reference measure situated in the plane of motion was also recorded on video following each subject’s data collection session.
Figure 1. Data collection set-up

Camera: lens height = 1.01m
Distance to subject = 5.55m
300W Lamp

Force Plate
Field of View: 1.90 m
Participant
Barbell
Weight Plate

Researcher at Desk with Computer

300W Lamp

computer
E&VCU
Sony MiniDV recorder

video in
video out
video in
video out
Kinematic data acquisition and processing

Once the data collection sessions were completed, the video record of each trial was recorded from the mini-DV recorder to the computer by the Peak MOTUS system. The digital video record of each trial on the computer was then cropped and synchronized to the corresponding ground reaction force data. The video records of the reference measure and force platform location were also recorded from the mini-DV recorder to the computer.

**Digitizing procedure.** The reference measure was manually digitized three times to calibrate the subsequent digitized coordinate data. The front and back of the force platform were also digitized so that the digitized coordinate data and the center of pressure data from the force platform could both be transformed to the same coordinate system.

The video-records of the lifting trials were then digitized using the automatic tracking function of the Peak MOTUS software. The following points on the left side of the body were tracked in each trial: TTIP, HEEL, AJC, KJC, HJC, SJC, and WB.

**Coordinate data filtering and transformation.** Once the raw coordinate data for a full trial were acquired from the video-record, the raw coordinates were smoothed using a fourth order Butterworth filter with a cut-off frequency of 7 hz. The resulting filtered coordinate data were then transformed to real life coordinates by multiplying each coordinate value by the ratio of the length of the reference measure to the digitized length of the reference measure. The raw coordinate system was then transformed to match the coordinate system of the force platform.

**Derived coordinate data.** Coordinates of the centers of gravity of the body segments were then computed from the coordinates of the body segment endpoints using
anthropometric data adopted from Zatsiorsky as adjusted by de Leva (1996). The pertinent body segment parameters from Zatsiorsky as adjusted by de Leva (1996) are shown in table 1. Body segments include the foot, with endpoints identified by the heel (HEEL) and the tip of the longest toe (TTIP); the shank, from the knee joint center (KJC) to the Lateral Malleolus (LMAL); the thigh, from the hip joint center (HJC) to the KJC; and the trunk, from midway between the shoulder joints (MIDS) to midway between the HJC’s (MIDH).

Table 2. *Body segment parameters from de Leva (1996).*

<table>
<thead>
<tr>
<th>Segment</th>
<th>Endpoints</th>
<th>Origin</th>
<th>Other</th>
<th>Mass (%)</th>
<th>Longitudinal CM position (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>M</td>
<td>F</td>
<td>M</td>
</tr>
<tr>
<td>Foot</td>
<td>HHEEL</td>
<td>1.29</td>
<td>1.37</td>
<td>40.14</td>
<td>44.15</td>
</tr>
<tr>
<td>Shank</td>
<td>KJC</td>
<td>4.81</td>
<td>4.33</td>
<td>44.16</td>
<td>44.59</td>
</tr>
<tr>
<td>Thigh</td>
<td>HJC</td>
<td>14.78</td>
<td>14.16</td>
<td>36.12</td>
<td>40.95</td>
</tr>
<tr>
<td>Trunk</td>
<td>MIDS</td>
<td>42.57</td>
<td>43.46</td>
<td>37.82</td>
<td>43.10</td>
</tr>
</tbody>
</table>

Table 3. *Radii of gyration of segments from de Leva (1996).*

<table>
<thead>
<tr>
<th>Segment</th>
<th>Sagittal $r$ (%)</th>
<th>Transverse $r$ (%)</th>
<th>Longitudinal $r$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>M</td>
<td>F</td>
</tr>
<tr>
<td>Foot</td>
<td>29.9</td>
<td>25.7</td>
<td>27.9</td>
</tr>
<tr>
<td>Shank</td>
<td>26.7</td>
<td>25.1</td>
<td>26.3</td>
</tr>
<tr>
<td>Thigh</td>
<td>36.9</td>
<td>32.9</td>
<td>36.4</td>
</tr>
<tr>
<td>Trunk</td>
<td>37.9</td>
<td>38.4</td>
<td>36.1</td>
</tr>
</tbody>
</table>
The location of the L3/L4 junction of the lumbar spine was determined from the coordinates of the HJC and SJC. According to Lariviere and Gagnon (1999), the L3/L4 junction lies in the same transverse plane as the omphalion (navel). Using the anthropometric data of Zatsiorsky as adjusted by de Leva (1996), the omphalion and respectively the L3/L4 junction is the origin of the LPT segment and represents a longitudinal length of 145.7 mm for the average male. The total trunk segment represents a longitudinal length of 515.5 mm from HJC to SJC for the average male. Based on these values, the longitudinal length of the L3/L4 junction from the HJC was computed as 28.26% of the entire trunk length from the HJC ((145.7 mm / 515.5 mm) x 100%).

**Velocities and accelerations**

The instantaneous linear and angular velocities and accelerations of the segment endpoints as well as the segment centers of gravity were computed from the filtered coordinate data. The first central difference method will be used to compute the velocities and accelerations at each 1/60 s time interval.

**Inverse Dynamic Analysis**

An inverse dynamic analysis of the lower body was conducted to determine the resultant joint torques and resultant joint forces at the transverse plane of the 3rd and 4th lumbar vertebrae. Before the inverse dynamic analysis was completed, the data from the force platform, which included vertical ground reaction forces, antero-posterior ground reaction forces, medial-lateral ground reaction forces, and coordinates of the center of pressure, had to be matched with the kinematic data. Since the kinematic data were sampled at 60 hz and the force data were sampled at 600 hz, ten consecutive force
measures, represented forces occurring during a 1/60 second interval, were averaged and matched to each kinematic data sample.

The inverse dynamic analysis used the two-dimensional model shown in figure 2 to represent both left and right lower extremities and the lower trunk of a subject. The analysis began with the foot segment and the ground reaction forces acting on the foot. The mass of the foot, radius of gyration of the foot, coordinates of the center of pressure, foot’s center of gravity, and ankle joint, along with the linear and angular acceleration of the foot’s center of gravity were input parameters to the equation of motion used to compute the horizontal and vertical resultant joint forces and the resultant joint torque at the ankle joint. These resultant joint forces and resultant joint torque were then used as input parameters along with the mass, radius of gyration, and coordinate and acceleration data for the ankle and knee joints and the center of gravity of the shank to the equations of motion used to compute the horizontal and vertical resultant joint forces and the resultant joint torque at the knee joint. The same procedure was repeated for the thigh to determine the horizontal and vertical resultant joint forces and the resultant joint torque at the hip joint. The procedure was repeated one more time for the lower trunk segment to determine the horizontal and vertical resultant joint forces and the resultant joint torque at the L3/L4 junction. The segment masses and radii of gyration were computed from data presented by Zatsiorsky as adjusted by de Leva (1996). These body segment parameters are presented in tables 2 and 3.

The angle of the trunk (from hip to shoulder) from horizontal and the horizontal and vertical resultant forces were used to calculate the resultant joint shear force and the resultant joint compressive force at the L3/L4 junction. The equations for computing
resultant joint forces and resultant torques can be found in Appendix E. All of these calculations were completed using Microsoft Excel.

Instantaneous power produced by the participant was derived from the vertical reaction force from the force platform and the mass of the participant plus the weighted barbell. Power can be expressed as force multiplied by velocity. In this case, the force is the vertical reaction force as measured by the force platform and velocity represents the instantaneous velocity of the center of gravity of the participant and barbell. The equations for computing power output are shown in appendix E.
Figure 2. Model used to compute the resultant shear force, resultant compressive force, and resultant torques at the transverse plane of the 3rd and 4th lumbar vertebrae.
Statistical Analysis

In order to determine significance, if any, paired t-tests were performed to assess the results. The dependent variables were the peak resultant torque, resultant shear force, and resultant compressive force at the transverse plane of the 3rd and 4th vertebrae of the lumbar spine and the maximum instantaneous power output. The independent variables are the 40% resistance and the 80% resistance. All statistical analyses were conducted using Stata, version 12.
CHAPTER 4
RESULTS AND DISCUSSION

The purpose of this study was to compare the peak resultant torque (T), peak resultant shear force (SF), and peak resultant compressive force (CF) acting on the L3/L4 junction of the lumbar spine during 40% 1RM and 80% 1RM attempts of the power clean and to determine the maximum instantaneous power output (POW) of each attempt. Participants performed the lifts on a force plate and were video recorded. The peak resultant torque, forces, and power outputs were computed using a combination of force plate data and static equilibrium equations.

Results

To simplify the interpretation of the peak resultant torque values at the L3/L4 junction, extensor torques were represented by positive values. Likewise, peak resultant shear forces were represented by positive values if the resultant shear force was directed anteriorly on the superior segment (L3) and posteriorly on the inferior segment (L4). Paired sample t-tests were used to compare the mean peak resultant torque, mean peak resultant forces, and mean peak instantaneous power outputs between 40% 1RM attempts and 80% 1RM power clean attempts. There was a significant difference between the peak resultant torque at 40% (M = 285 Nm, SD = 46 Nm) attempts and peak resultant torque at 80% (M = 432 Nm, SD = 505 Nm) attempts; t (7) = 4.248, p = 0.0038. There was also significant difference between the peak resultant shear force at 40% (M = 847 N, SD = 623 N) attempts and peak resultant shear force at 80% (M = 1386 N, SD = 201 N) attempts; t (7), p = 0.0171. There was a significant difference between the peak...
resultant compressive force at 40% (M = 1020 N, SD = 322 N) attempts and peak resultant compressive force at 80% (M = 1519 N, SD = 231 N) attempts; t (7) = 4.952, p = 0.0017. There was also a significant difference between the peak instantaneous power output at 40% (M = 2206 W, SD = 520 W) attempts and the peak instantaneous power output at 80% (M = 2695 W, SD = 500 W) attempts; t (7) = 2.764, p = 0.0279.

Table 4. Summary of values for each variable.

<table>
<thead>
<tr>
<th>Variable</th>
<th>n</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>40% T (Nm)</td>
<td>8</td>
<td>285</td>
<td>46</td>
<td>353</td>
<td>234</td>
</tr>
<tr>
<td>40% SF (N)</td>
<td>8</td>
<td>848</td>
<td>624</td>
<td>1210</td>
<td>667</td>
</tr>
<tr>
<td>40% CF (N)</td>
<td>8</td>
<td>1021</td>
<td>322</td>
<td>742</td>
<td>1704</td>
</tr>
<tr>
<td>40% POW (W)</td>
<td>8</td>
<td>2207</td>
<td>521</td>
<td>1552</td>
<td>2916</td>
</tr>
<tr>
<td>80% T (Nm)</td>
<td>8</td>
<td>433</td>
<td>87</td>
<td>574</td>
<td>334</td>
</tr>
<tr>
<td>80% SF (N)</td>
<td>8</td>
<td>1387</td>
<td>201</td>
<td>1623</td>
<td>1067</td>
</tr>
<tr>
<td>80% CF (N)</td>
<td>8</td>
<td>1519</td>
<td>231</td>
<td>1121</td>
<td>1723</td>
</tr>
<tr>
<td>80% POW (W)</td>
<td>8</td>
<td>2695</td>
<td>476</td>
<td>2117</td>
<td>3557</td>
</tr>
</tbody>
</table>

Note. T = peak torque, SF = peak shear force, CF = peak compressive force, POW = peak power.

Table 5. Summary of statistical analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>t</th>
<th>DF</th>
<th>p</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>4.24</td>
<td>7</td>
<td>0.004</td>
<td>1.5</td>
</tr>
<tr>
<td>Shear</td>
<td>3.10</td>
<td>7</td>
<td>0.017</td>
<td>1.75</td>
</tr>
<tr>
<td>Compression</td>
<td>4.95</td>
<td>7</td>
<td>0.002</td>
<td>1.10</td>
</tr>
<tr>
<td>Power</td>
<td>2.76</td>
<td>7</td>
<td>0.028</td>
<td>.98</td>
</tr>
</tbody>
</table>
Figure 3. Peak Resultant Torque

Figure 4. Peak Resultant Shear Force
Figure 5. Peak Resultant Compressive Force

Figure 6. Peak Instantaneous Power
**Discussion**

The results of this study were limited by the accuracy of the points during digitization due to reflective markers being obstructed in the camera views, a small sample size, the assumption that all participants put forth maximal effort, the accuracy of each participant’s self determined one repetition maximum, and the participation of only collegiate track and field males. It is also important to note that data from eight participants was used rather than nine because of an error with video recording.

Based upon the results of this study it is evident that the 80% 1RM loads resulted in significantly higher peak torque, compressive, and shear forces than that of the 40% 1RM loads (Table 4). It is also evident that the 80% 1RM resulted in significantly higher power outputs than that of the 40% 1RM (See Table 4). Individual participant data for each variable can be found above in figures 3-6.

The significantly larger mean shear force and mean compressive force at 80% 1RM when compared to 40% 1RM is supported by previous research done by Hall (1985), though it should be noted that the exercise performed in that study was the clean and jerk rather than the power clean. It should also be noted that this study showed significant differences in mean torque as well when the study done by Hall (1985) did not. The results of this study are also consistent with research done by Lavender, Andersson, Schipplein, and Fuentes (2003). In their study examining the effects of lifting height, magnitude, and speed on L5/S1 moments they found significantly higher peak moments with heavier loads. While this study was mainly focused on occupational safety it still holds relevance for a sports training situation because of the inclusion of various loads and lifting speeds.
Based on the statistics from table 5 and the apparent relationships shown in figures 3-6 it is obvious that an increase in load will result in an increase in torque, shear, and compressive forces on the L3/L4 junction of the lumbar spine. It is also obvious that a significant increase in power output will occur from 40% to 80%. However, this increase in power from 40% to 80% 1RM, while significant, is not nearly as large as the increase in the peak forces and torque at the L3/L4 junction shown from 40% to 80% 1RM. During the power clean at 80% 1RM the peak compressive force exerted on the L3/L4 junction increased by nearly 50% when compared to the 40% 1RM but power output only increased by about 22% (see figure 7). This could place into question the benefit of using heavier loads during the power clean because the 22% power increase is paired with a much higher and potentially harmful 50% increase in compressive force on the L3/L4. These results are somewhat of a concern because it is a common goal of sports training using power lifting to increase power, and increasing the load will result in increased power but will also increase forces exerted on an injury prone part of the lumbar spine.
Figure 7. Percent Increases for Dependent Variables
Summary

The purpose of this study was to compare the peak resultant torque, peak resultant shear force, and peak resultant compressive force that is exerted on the L3/L4 junction of the lumbar spine during a power clean at 40% 1RM and 80% 1RM and to determine the respective maximum instantaneous power outputs. It was hypothesized that the forces would be significantly greater during the 80% 1RM than those during the 40% 1RM and that the maximum instantaneous power output would be greater during the 80% 1RM than the 40% 1RM. Participants were nine Division III male varsity track and field athletes who had at least two years of experience performing the power clean during their mandatory sports training regimens. Each participant performed the power clean on a force plate and each attempt was video recorded. Peak forces and power outputs were calculated using data collected from the force plate and kinematic data. Statistical analyses revealed that the mean peak torque, peak shear force, peak compressive force, and peak power were significantly greater during the 80% 1RM attempts.

Conclusions

Results of this study show concrete evidence that a power clean at 80% 1RM will lead to significantly greater torque, shear force, compressive force, and power output than that of a 40% 1RM.
**Implications**

These results show that significant forces are exerted on an area of the body that has long been known to be susceptible to injury. Rossi and Dragoni (1990) revealed that 22.7% of 97 weight lifters studied had lumbar spondylolysis and suggested that the symptoms were related to repetitive, forced, hyperextension lumbar movements. This type of movement is the embodiment of an exercise such as the power clean. Exercises such as the power clean should be done with great care and attention to technique from a qualified professional. It can be assumed that better technique may result in less forces exerted on the L3/L4 junction but further research is necessary to be sure. It can also be assumed that using a heavier load may result in an increase in power output, but the percent increase in power is much less than the percent increase in force exerted on the L3/L4 junction, at least between 40% and 80% 1RM loads. This larger percentage of increase in force at the L3/L4 could result in an increased susceptibility to injury.

**Suggestions**

Future research should focus on comparing the same or similar variables between Olympic lifters who have excellent technique and participants with similar lifting experience to the participants used in this study. Inclusion of professional power lifters could display a much needed emphasis on attention to detail and technique to those teaching the exercise for sports training purposes. The comparison of professionals with those who are only somewhat experienced is necessary to determine differences in technique and how this affects the forces exerted on injury susceptible areas of the body. Future research should also include many more subjects, use only attempts that are approved by a professional for data collection, allow each participant more attempts at
each load, use better reflectors that will not fall off during the exercise to make the
digitization process more accurate and easier, and have a pre-test to determine 1RM
rather than them being self-identified.
References


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APPENDIX A

State University of New York College at Cortland
Informed Consent

The research in which you have been invited to participate is being conducted by graduate student Joseph Keleher of the Kinesiology Department at SUNY Cortland. The researcher requests your informed consent to be a participant in the project described below. This project has the purpose of comparing the forces exerted on the L3/L4 junction of the lumbar spine during power cleans at 40% and 80% one repetition maximum. Please feel free to ask about the project, its procedures, or objectives.

You will be asked to execute a power clean at 40% and 80% of your estimated one repetition maximum. The researcher will place markers on your left heel, toe, ankle joint, knee joint, hip joint, and shoulder joint. Your performance will be videotaped. This will take place in one session that will last approximately an hour. The opportunity to participate in this study will be made available to approximately 10 male SUNY Cortland Track and Field athletes.

The risks associated with your participation in this study are minimal. However, there is always a risk of injury associated with engaging in physical activity. Only the researcher will have access to your videotaped performances. Your videotaped performances will be saved on a flash drive containing your subject ID#. This flash drive and all other data will be stored in a locked cabinet in the Biomechanics Lab for no more than 3 years, upon which all videos will be deleted and all paper documents will be shredded. At no time will your name be associated with the data results. Only group aggregate scores will be reported.

You are free to withdraw consent at any time without penalty. Additionally, at any time, you may ask the researcher to destroy all videotape recordings of your performances, as well as any other data or information collected.

From participating in this study, you should expect to come to a better understanding of the way in which research is conducted.

If you have any questions concerning the purpose or results of this study, you may contact Joseph Keleher at (716) 545-5616 or at joseph.keleher@Cortland.edu. Other contacts include: Dr. Peter McGinnis, Professor of Kinesiology at (607) 753-4909 or peter.mcginnis@Cortland.edu. For questions about research at SUNY Cortland or questions/concerns about participant rights and welfare, you may contact The SUNY Cortland Institutional Review Board, PO Box 2000, Cortland, NY, 13045 (phone (607) 753-2511 or email irb@cortland.edu). In the event of an injury please contact the SUNY Cortland Counseling Center in room B-44 Van Hoesen Hall (607) 753-4728, and/or SUNY Cortland Health Center in room B-26 of Van Hoesen Hall at (607) 753-4811.

I (print name) __________________________________ have read the description of the project for which this consent is requested, understand my rights, and I hereby consent to participate in this study.

Signature: ____________________________ Date: ____________________
APPENDIX B

Physical Activity Readiness Questionnaire (PAR-Q)

Please answer the following questions honestly by placing an “X” in the appropriate space. Honest answers to these questions will help in determining your readiness to participate.

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor? Y__ N__
2. Do you feel pain in your chest when you do physical activity? Y__ N__
3. In the past month, have you had chest pain when you were not doing physical activity? Y__N__
4. Do you lose your balance because of dizziness or do you ever lose consciousness? Y__ N__
5. Do you have a done or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity? Y__ N__
6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition? Y__ N__
7. Do you know of any other reason why you should not do physical activity? Y__ N__

If you answered yes to one or more of these questions, see your doctor before you start becoming much more physically active or before you have a fitness appraisal.

From [http://www.acsm.org/docs/current-comments/whentoseeadoctortemp.pdf](http://www.acsm.org/docs/current-comments/whentoseeadoctortemp.pdf)
APPENDIX C

Participant Information Questionnaire (PIQ)

Please respond to the following questions as accurately as possible.

For the Participant

Subject ID# ______

Have you recently sustained any injury that may impose your ability to participate? Y___
N___

Age ______

Weight ______

Height ______

Years of experience performing the power clean during your standard training regimen

_____

Maximum load _____ for _____ repetitions

For the researcher

Calculated 1RM _____

Estimated 40% 1RM _____

Estimated 80% 1RM _____
APPENDIX D

SUNY Cortland Institutional Review Board Approval Letter

MEMORANDUM

To: Joseph A. Keeler
     Peter McGinnis

From: Irena Vincent, Primary reviewer on behalf of
       Institutional Review Board

Date: 11/27/2012

RE: Institutional Review Board Approval

In accordance with SUNY Cortland’s procedures for human research participant protections, the protocol referenced below has been approved for a period of one year.

Title of the study: Comparison of forces Exerted on the Lumbar Spine During the Power Clean Exercise

Level of review: Expedited

Protocol number: 1213

Project start date: Upon IRB approval

Approval expiration date*: 11/26/2013

* Note: Please include the protocol expiration date to the bottom of your consent form and recruitment materials.

For more information about continuation policies and procedures, visit www.cortland.edu/irb/Applications/continuations.html.

The federal Office for Research Protections (ORRP) emphasizes that investigators play a crucial role in protecting the rights and welfare of human subjects and are responsible for carrying out sound ethical research consistent with research plans approved by an IRB. Along with meeting the specific requirements of a particular research study, investigators are responsible for ongoing requirements in the conduct of approved research that include, in summary:

- obtaining and documenting informed consent from the participants and/or from a legally authorized representative prior to the individuals’ participation in the research, unless these requirements have been waived by the IRB;
- obtaining prior approval from the IRB for any modifications of (or additions to) the previously approved research; this includes modifications to advertisements and other recruitment materials, changes to the informed consent or child assent, the study design and procedures, addition of research staff or student assistants, etc. (except those alterations necessary to eliminate apparent immediate hazards to subjects, which are then to be reported by email to irb@cortland.edu within three days);
- providing to the IRB prompt reports of any unanticipated problems involving risks to subjects or others;
- notifying the IRB of continued research under the approved protocol to keep the records active; and,
- maintaining records as required by the HHS regulations and NY’s State law, for at least three years after completion of the study.
In the event that questions or concerns arise about research at SUNY Cortland, please contact the IRB by email irb@cornell.edu or by telephone at (607)753-2511. You may also contact a member of the IRB who possesses expertise in your discipline or methodology, visit http://www.cornell.edu/irb/members.html to obtain a current list of IRB members.

Sincerely,

Irene Vincent, Primary reviewer on behalf of
Institutional Review Board
SUNY Cortland
APPENDIX E

Calculation of resultant joint forces, torque, and power

ANKLE JOINT – resultant forces and torque acting on foot at ankle joint.

Resultant Horizontal Force at the Ankle: $\mathbf{R}_{ax}$

$$\sum F_x = R_x - R_{ax} = m_f a_{fx}$$

$$R_{ax} = R_x - m_f a_{fx}$$

where,

- $R_x$ = horizontal ground reaction force
- $m_f$ = mass of the foot
- $a_{fx}$ = horizontal acceleration of the foot

Resultant Vertical Force at the Ankle: $\mathbf{R}_{ay}$

$$\sum F_y = R_y - R_{ay} - W = m_f a_{fy}$$

$$R_{ay} = R_y - W - m_f a_{fy}$$

where,

- $R_y$ = vertical ground reaction force
- $W$ = weight of the foot
- $m_f$ = mass of the foot
- $a_{fy}$ = vertical acceleration of the foot

Resultant Joint Torque at Ankle Joint: $\mathbf{T}_a$

$$\sum T_{cg} = R_x (y_{fcg} - y_{cp}) - R_y (x_{fcg} - x_{cp}) + R_{ax} (y_a - y_{fcg}) - R_{ay} (x_a - x_{fcg}) - T_a = I_f \alpha_f$$

$$T_a = - I_f \alpha_f + R_x (y_{fcg} - y_{cp}) - R_y (x_{fcg} - x_{cp}) + R_{ax} (y_a - y_{fcg}) - R_{ay} (x_a - x_{fcg})$$

where,

- $I_f$ = moment of inertia of the foot
$\alpha_f$ = angular acceleration of the foot around its center of gravity

$R_x =$ horizontal ground reaction force

$y_{fcg} =$ vertical coordinate of the foot’s center of gravity

$y_{cp} =$ vertical coordinate of the foot’s center of pressure on the force platform $= 0$

$R_y =$ vertical ground reaction force

$x_{fcg} =$ horizontal coordinate of the foot’s center of gravity

$x_{cp} =$ horizontal coordinate of the foot’s center of pressure on the force platform

$R_{ax} =$ horizontal reaction force at the ankle

$y_a =$ vertical coordinate of the ankle

$y_{fcg} =$ vertical coordinate of the foot’s center of gravity

$R_{ay} =$ vertical reaction force at the ankle

$x_a =$ horizontal coordinate of the ankle

$x_{fcg} =$ horizontal coordinate of the foot’s center of gravity

**KNEE JOINT - resultant forces and torque acting on lower leg at knee joint.**

**Resultant Horizontal Force at the Knee Joint: $R_{ax}$**

$\Sigma F_x = R_{ax} - R_{kx} = m_a a_{sx}$

$R_{kx} = R_{ax} - m_a a_{sx}$

where,

$R_{ax} =$ horizontal reaction force from the ankle

$m_a =$ mass of the shank

$a_{sx} =$ horizontal acceleration of the shank

**Resultant Vertical Force at the Knee Joint: $R_{ky}$**

$\Sigma F_y = R_{sy} - R_{kx} - W = m_a a_{sy}$
\[ R_{ky} = R_{sy} - W - m_s a_{sy} \]

where,

- \( R_{sy} \) = vertical reaction force from the ankle
- \( W \) = weight of the shank
- \( m_s \) = mass of the shank
- \( a_{sy} \) = vertical acceleration of the shank

**Resultant Joint Torque at Knee Joint: \( T_k \)**

\[
\Sigma T_{cg} = R_{ax} (y_{scg} - y_a) - R_{sy} (x_{scg} - x_a) + R_{ax} (y_k - y_{scg}) - R_{ky} (x_k - x_{scg}) + T_a - T_k = I_s \alpha_s
\]

\[
T_k = -I_s \alpha_s + T_a + R_{ax} (y_{scg} - y_a) - R_{sy} (x_{scg} - x_a) + R_{ax} (y_k - y_{scg}) - R_{ky} (x_k - x_{scg})
\]

where,

- \( I_s \) = moment of inertia of the shank
- \( \alpha_s \) = angular acceleration of the shank around its center of gravity
- \( R_{ax} \) = horizontal reaction force from the ankle
- \( y_{scg} \) = vertical coordinate of the shank’s center of gravity
- \( y_a \) = vertical coordinate of the ankle
- \( R_{sy} \) = vertical reaction force from the ankle
- \( x_{scg} \) = horizontal coordinate of the shank’s center of gravity
- \( x_a \) = horizontal coordinate of the ankle
- \( R_{ax} \) = horizontal reaction force at the ankle
- \( y_a \) = vertical coordinate of the ankle
- \( y_{scg} \) = vertical coordinate of the shank’s center of gravity
- \( R_{sy} \) = vertical reaction force at the ankle
- \( x_a \) = horizontal coordinate of the ankle
x_{scg} = horizontal coordinate of the shank’s center of gravity

**HIP JOINT - resultant forces and torque acting on thigh at hip joint.**

**Resultant Horizontal Force at the Hip Joint: R_{hx}**

\[ \Sigma F_x = R_{kx} - R_{hx} = m_t a_x \]
\[ R_{hx} = R_{kx} - m_t a_x \]

where,

- \( R_{kx} \) = horizontal reaction force from the knee
- \( m_t \) = mass of the thigh
- \( a_x \) = horizontal acceleration of the thigh

**Resultant Vertical Force at the Hip Joint: R_{hy}**

\[ \Sigma F_y = R_{ky} - R_{hy} - W = m_t a_y \]
\[ R_{hy} = R_{ky} - W - m_t a_y \]

where,

- \( R_{ky} \) = vertical reaction force from the knee
- \( W \) = weight of the thigh
- \( m_t \) = mass of the thigh
- \( a_y \) = vertical acceleration of the thigh

**Resultant Joint Torque at Hip Joint: T_{h}**

\[ \Sigma T_{cg} = R_{kx} (y_{tcg} - y_k) - R_{ky} (x_{tcg} - x_k) + R_{hx} (y_h - y_{tcg}) - R_{hy} (x_h - x_{tcg}) + T_k - T_{h} = I_t \alpha_t \]
\[ T_{h} = -I_t \alpha_t + T_k + R_{kx} (y_{tcg} - y_k) - R_{ky} (x_{tcg} - x_k) + R_{hx} (y_h - y_{tcg}) - R_{hy} (x_h - x_{tcg}) \]

where,

- \( I_t \) = moment of inertia of the thigh
- \( \alpha_t \) = angular acceleration of the thigh around its center of gravity
\( R_{kx} \) = horizontal reaction force from the knee
\( y_{tcg} \) = vertical coordinate of the thigh’s center of gravity
\( y_k \) = vertical coordinate of the knee
\( R_{ky} \) = vertical reaction force from the knee
\( x_{tcg} \) = horizontal coordinate of the thigh’s center of gravity
\( x_k \) = horizontal coordinate of the knee
\( R_{kx} \) = horizontal reaction force at the knee
\( y_k \) = vertical coordinate of the knee
\( y_{tcg} \) = vertical coordinate of the thigh’s center of gravity
\( R_{ky} \) = vertical reaction force at the knee
\( x_k \) = horizontal coordinate of the knee
\( x_{tcg} \) = horizontal coordinate of the thigh’s center of gravity

**L3/L4 Junction - resultant forces and torque acting on the lower trunk at the L3/L4**

**Resultant Horizontal Force at the L3/L4:** \( R_{L3/L4x} \)

\[
\Sigma F_x = R_{hx} - R_{L3/L4x} = m_{LT} a_{LTx}
\]

\( R_{L3/L4x} = R_{hx} - m_{LT} a_{LTx} \)

where,

- \( R_{hx} \) = horizontal reaction force from the hip
- \( m_{LT} \) = mass of the lower part of the trunk
- \( a_{LTx} \) = horizontal acceleration of the lower part of the trunk

**Resultant Vertical Force at the L3/L4:** \( R_{L3/L4y} \)

\[
\Sigma F_y = R_{hy} - R_{L3/L4y} - W = m_{LT} a_{LTy}
\]

\( R_{L3/L4y} = R_{hy} - W - m_{LT} a_{LTy} \)
where,

\[ R_{by} = \text{vertical reaction force from the hip} \]
\[ W = \text{weight of the lower trunk} \]
\[ m_{LT} = \text{mass of the lower trunk} \]
\[ a_{LTy} = \text{vertical acceleration of the lower trunk} \]

**Resultant Joint Torque at L3/L4: \( T_{L3/L4} \)**

\[
\Sigma T_{cg} = R_{hx} (y_{LTcg} - y_h) - R_{by} (x_{LTcg} - x_h) + R_{L3/L4x} (y_{L3/L4} - y_{LTcg}) - R_{L3/L4y} (x_{L3/L4} - x_{LTcg})
+ T_h - T_{L3/L4} = I_{LT} a_{LT}
\]

\[
T_{L3/L4} = -I_{LT} a_{LT} + T_h + R_{hx} (y_{LTcg} - y_h) - R_{by} (x_{LTcg} - x_h) + R_{L3/L4x} (y_{L3/L4} - y_{LTcg}) - R_{L3/L4y} (x_{L3/L4} - x_{LTcg})
\]

where,

\[ I_{LT} = \text{moment of inertia of the lower trunk} \]
\[ a_{LT} = \text{angular acceleration of the thigh around its center of gravity} \]
\[ R_{hx} = \text{horizontal reaction force from the hip} \]
\[ y_{LTcg} = \text{vertical coordinate of the lower trunk’s center of gravity} \]
\[ y_h = \text{vertical coordinate of the hip} \]
\[ R_{by} = \text{vertical reaction force from the hip} \]
\[ x_{LTcg} = \text{horizontal coordinate of the lower trunk’s center of gravity} \]
\[ x_h = \text{horizontal coordinate of the hip} \]
\[ R_{L3/L4x} = \text{horizontal reaction force at the L3/L4 junction} \]
\[ y_{L3/L4} = \text{vertical coordinate of the L3/L4 junction} \]
\[ y_{LTcg} = \text{vertical coordinate of the lower trunk’s center of gravity} \]
\[ R_{L3/L4y} = \text{vertical reaction force at the L3/L4 junction} \]
\[ x_{L3/L4} = \text{horizontal coordinate of the L3/L4 junction} \]
\[ x_{LTcg} = \text{horizontal coordinate of the lower trunk’s center of gravity} \]

**Compressive Force at L3/L4:** \( R_c \)

\[ R_c = R_{L3/L4y} \sin \theta - R_{L3/L4x} \cos \theta \]

where,
\[ R_{L3/L4y} = \text{vertical reaction force at the L3/L4 junction} \]
\[ R_{L3/L4x} = \text{horizontal reaction force at the L3/L4 junction} \]
\[ \theta = \text{angle from horizontal of the trunk from the hip to the shoulder} \]

**Shear Force at L3/L4:** \( R_s \)

\[ R_s = R_{L3/L4x} \sin \theta + R_{L3/L4y} \cos \theta \]

where,
\[ R_{L3/L4y} = \text{vertical reaction force at the L3/L4 junction} \]
\[ R_{L3/L4x} = \text{horizontal reaction force at the L3/L4 junction} \]
\[ \theta = \text{angle from horizontal of the trunk from the hip to the shoulder} \]

**Maximum Instantaneous Power:** \( P \)

\[ P = Fv \]

where,
\[ F = \text{Force} = R_y = \text{vertical reaction force from force platform} \]
\[ v = \text{vertical velocity of center of gravity athlete plus loaded barbell} \]

The mass of the participant plus the loaded barbell was multiplied by the acceleration due to gravity and subtracted from the vertical reaction force to determine the net force acting on the participant plus loaded barbell:

\[ \Sigma F = F - W = (F - (mg)) \]
where,

\[ \sum F = \text{net vertical force acting on participant plus loaded barbell} \]

\[ F = \text{vertical reaction force measured by force platform} \]

\[ m = \text{mass of participant plus barbell} \]

\[ W = \text{weight of participant and barbell} \]

\[ g = 9.81\text{m/s}^2 = \text{acceleration due to gravity} \]

Change in velocity of the participant plus weighted barbell was determined using the following formula:

\[ \Delta v = a \Delta t = \frac{(\sum F) \Delta t}{m} = \frac{(F - mg) \Delta t}{m} \]

where,

\[ \Delta v = \text{change in vertical velocity during the sampling time} \]

\[ a = \text{vertical acceleration of the participant plus weighted barbell} \]

\[ \Delta t = \text{sample time} = \frac{1}{60} \text{s} \]

\[ F = \text{vertical reaction force measured by force platform} \]

\[ m = \text{mass of the participant plus weighted barbell} \]

Instantaneous vertical velocity was calculated by adding the \( \Delta v \) value to the instantaneous velocity of the previous sample. The initial velocity of the participant and barbell at the beginning of the lift was assumed to be zero.

\[ v_i = v_{i-1} + \Delta v = v_{i-1} + \left( \frac{(F_i - mg) \Delta t}{m} \right) \]

where,

\[ v_i = \text{vertical velocity of the participant plus barbell at time } i \]

\[ v_{i-1} = \text{vertical velocity of the participant plus barbell at time } i-1 \]
$$F_i = \text{vertical reaction force measured by force platform at time } i$$

The instantaneous velocity was multiplied by force to determine instantaneous power:

$$P_i = (F_i)(v_i) = (F_i) \left\{ v_{i-1} + \frac{(F_i - mg) \Delta t}{m} \right\}$$

where,

$$P_i = \text{instantaneous power at time } i$$

$$F_i = \text{vertical reaction force measured by force platform at time } i$$

$$v_i = \text{vertical velocity of the participant plus barbell at time } i$$

$$v_{i-1} = \text{vertical velocity of the participant plus barbell at time } i-1$$