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Energetics of weightlifting and jump landing tasks

by

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ABSTRACT

The objective of this research was to study the work performed and distribution of work across the lower extremity in various landing tasks. Ten women performed jump landing and weightlifting tasks recorded in a motion analysis laboratory. Joint angles and moments were determined, from which work performed at the hip, knee and ankle, was calculated. Greater foot plantarflexion and less leg dorsiflexion at impact was found in the jump landing tasks, which corresponded with increased ankle work performed. More knee work was observed in the weightlifting tasks, which was explained by a higher knee extensor net joint moment (NJM). The percentage contribution of the knee to total work performed was the highest for all tasks. This research highlights the importance of knee extensor strength for absorbing energies during landing. As the weightlifting tasks demonstrated the greatest knee work and NJMs, these exercises may be most effective for enhancing knee extensor strength.

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CHAPTER I

INTRODUCTION

Investigating the manner in which the human body generates internal forces and responds to external forces is required to study coordinated movement (1). One particular area of interest is to understand how the musculoskeletal system attenuates the high impact forces applied to the body during certain activities, such as landing from a jump. During these impact activities, muscular work must be performed due to the kinetic energy present at impact. To determine how muscles function during multi-joint tasks to absorb energy, motion analysis techniques can be applied to estimate the work performed by different muscle groups (19). The work performed by muscles on joints has been studied across a variety of multi-joint tasks, such as gait (20). However, the pattern of energy absorption across segments and joints during landing has received little attention. As different types of landings are possible (3), it is important to understand how variation in landing techniques influences the distribution of work performed in the musculoskeletal system.

WORK-ENERGY THEOREM

Based on the first law of thermodynamics, the energy in a system cannot be created or destroyed, rather it can be changed from one form to another. During landing, after falling from a height, the contribution of kinetic and potential energy to the total energy of the system is determined by the displacement of the body's centre of mass (COM). As the body gains kinetic energy when falling, work must be performed from the instant of impact to reduce the velocity of the body to zero following the impact. The higher the height of the fall results in greater kinetic energy present at impact and, therefore, the body must perform more work.

To determine the amount of work completed during landing, the change in total mechanical energy must be considered from the initial drop height (or maximal vertical displacement) to the lowest position (i.e. deepest squat position). The time between these distinct points can be divided into two phases: pre- and post-impact. The mechanical energy pre-impact is equivalent to the loss in potential energy, which equals the gain in kinetic energy (Figure 1 – 1). Post-impact, the body continues to lose potential energy as the COM continues to lower. The amount of work that must be performed is equal to the kinetic energy present at impact plus the additional loss of potential energy post-impact.

The change in kinetic and potential energies are primarily considered in the determination of muscular work performed during landing (19). However, elastic strain energy must also be considered. As a result of structural deformation of soft tissues (i.e. muscles, ligaments), energy may be stored and then released, which ultimately influences the amount of work performed. Without consideration of the elastic strain energy present as a consequence of tissue deformation, the amount of muscular work may be over or underestimated, depending on whether energy is stored or released. According to Robertson (19), it is difficult to compute the strain energy generated during multi-segment tasks because the amount of deformation is often small and techniques to measure elastic strain energy are costly. Although it is challenging to obtain an accurate measure of elastic strain energy, it must still be recognized as a source of error in the quantification of work performed during landing.

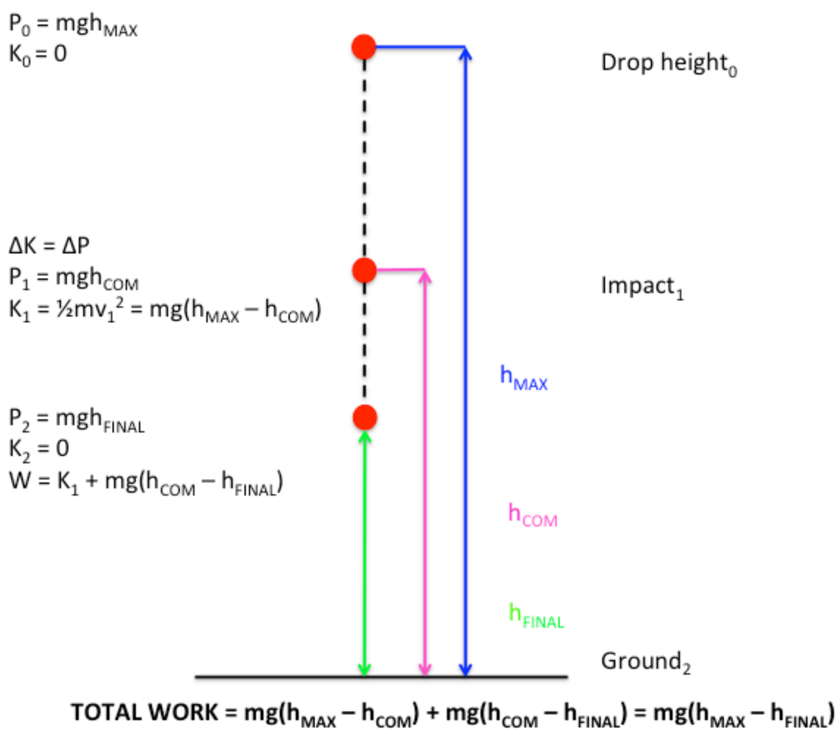


Figure 1 – 1: Change in mechanical energy during landing.

The change in kinetic and potential energies can be estimated using the point-mass model as shown in Figure 1 – 1. However, the point-mass model oversimplifies a multi-segment system as it only accounts for two types of energy: 1) translational kinetic energy and 2) gravitational potential energy (19). It also underestimates the mechanical energy (19), because it does not consider the musculoskeletal system as a system of rigid-body, linked segments. That being said, each segment contributes additional rotational kinetic energy to the system. The rotational energy can be transferred across segments to increase or decrease the system's total energy (19). These additional energies contributed by segments are not accounted for using the linear kinematics of a single point (i.e. COM). As a result, the total mechanical energy of the musculoskeletal system is inaccurate. Instead, another approach that accounts for this limitation is the segmental method. This method utilizes the segment kinematics and inertial parameters to determine the energy in the system (19). Although this method is more accurate than the point mass model, it is still not the best estimate of energy because it fails to account for the internal work performed by muscles. When only the external work is calculated, any changes (i.e. excess or loss) of internal work are not accounted for, which has been termed the zero-work paradox (19). This ultimately leads to an unreliable measure of the total mechanical energy of the system.

The absolute energy or mechanical energy approach (19) is an alternative method that does not carry the same limitations as the point mass and segmental methods. This method measures both the internal and external work performed. It also accounts for any transfer of energy between segments, and mechanical energy received by the segments from the work performed by muscles (19). Thus, the best estimate of work performed is achieved by summing the work performed on the segments and the work performed by the muscle, the latter of which is estimated through inverse dynamics techniques.

Through inverse dynamics, the muscular work performed during multi-joint tasks is a function of the net joint moment (NJM) and joint excursion. In terms of the energetics of a movement, the analysis of the joint and segment kinematics and kinetics are vital to understanding the absorption of energy during landing. Kinematics describe motion without regard to the causes of motion, whereas kinetics explain movement in relation to its causes (i.e. forces) (19). In the study of energetics, the primary kinematic variable of interest to explain how work is performed is joint excursion, which represents the change in displacement of the body in context of the joint and segment motions. In terms of kinetics, the main variable of interest is the NJM. The NJM is an estimate of the net muscular moment, which by definition is the contribution of all muscular torques including agonists and antagonists acting across a joint (17). Despite the fact that the NJM does not account for co-contraction, it is an important parameter to explain the contribution of muscles and muscle groups to a coordinated movement (17, 20).

To ensure the NJM and joint excursions are responsible for any increase or decrease in total mechanical energy, two assumptions must be met: 1) the musculoskeletal system is rigid and 2) joints are frictionless (19). While the human body in reality is not rigid since soft tissue structures are compressed or elongated during movement, for simplicity of analysis, it is assumed the length of a segment does not change and deformation of soft tissue structures is negligible (19). It is also assumed that there is no capsular damage is present to create friction between segments. If the above assumptions are not satisfied, energy may be presumed to be absorbed elsewhere, for example, from frictional losses and compression of the joint articulating surfaces (19). Through inverse dynamics, the pattern of energy absorption can be determined as it relates to the kinetics (i.e. NJMs) and kinematics (i.e. joint excursions) required to absorb the energy generated at impact. After consideration of all the methods available to quantify mechanical energy, it can be concluded that the inverse dynamics method is most superior to describe complex movements and to understand the energetics of multi-segment tasks.

LANDING TECHNIQUE

To absorb the impact forces created upon landing, either a soft- or stiff-landing technique can be employed. Kinematic analysis suggests that soft-landings are characterized by peak knee flexion angles greater than 90 degrees, whereas stiff-landings are performed with less than 90 degrees of knee flexion (10). Given that the work performed by muscles is a function of the muscular moment and joint excursion, soft-landings should allow work to be performed via large knee joint excursions while minimizing the knee extensor NJM. This implies that the maximum force applied to the knee extensor muscles is less than if a stiff-landing is performed. Stiff-landings, which have smaller knee joint excursions would require either greater knee extensor moments or, alternatively, more work could be performed by muscles crossing other joints. Bobbert et al. (3) found that drop jumps performed with less knee flexion resulted in higher peak knee extensor and ankle plantar-flexor moments. However, work performed at these joints was not reported. As differences in landing technique influence joint kinematics and kinetics, it is important to investigate how work performed is distributed across the lower extremity.

DeVita et al. (10) reported that the distribution of total work performed in the lower extremity differed between soft and stiff landings. During soft-landings, 25% of the lower extremity work was performed at the hip, 37% at the knee and 31% at the ankle. When landing with a stiff technique, the relative contributions to total work were 20, 31 and 51% at the hip, knee and ankle, respectively. Thus, landing with reduced knee flexion (less than 90° knee flexion), increased the amount of work performed at the ankle, and decreased the resulting work performed at the knee and hip. A study by Zhang et al. (21) found differences in landing energetics across a variety of landing techniques (i.e. soft, stiff and normal) and heights (0.32, 0.62 and 1.03 m). Greater work was found at the ankle for stiff landings, whereas more work was performed by the hip extensors at during the soft landings. Across all landing techniques, the knee extensors performed a large percentage of the work (~41 – 47%) and greater work was performed by the ankle plantar flexors and hip extensors with increased landing height. Kulas et al. (16) also found that manipulating trunk load influenced how work was distributed across the hip, knee and ankle. When a fitted weight vest applied 10% body weight to the trunk, two compensatory strategies were noted. In the participants who extended their trunk, decreased hip angular impulses and energy absorption were observed, whereas in participants who flexed their trunk, increased hip angular impulses and energy absorption were reported. This study also found that trunk load influences knee and ankle mechanics, where the percentage of work performed at the hip decreases, and a compensatory increase in work performed at the knee and ankle was noted.

Collectively, the aforementioned studies demonstrate that an externally applied load and landing technique influences the distribution of work performed across the lower extremity muscles. Investigating how load influences muscular work performed across the lower extremity may be used to understand how changes in body mass (i.e. weight gain or loss) affect landing mechanics. How muscular work is distributed across the lower extremities is also important when external loads are applied, such as in occupations where heavy equipment may be worn (i.e. firefighting) or when an implement is lifted, as in resistance exercise.

A task that has been compared to landing from a jump is the catch phase of weightlifting, where an external load is received overhead or on the shoulders. In the sport of weightlifting, the goal is to perform a single repetition at the highest possible load for the snatch and clean and jerk. Weightlifting presents a unique opportunity to explore how work is performed during landing-type tasks as 1) external loading is applied and 2) joint excursions can be manipulated. In terms of joint excursion, the barbell may be caught in a full or partial squat. Hence, the total muscular work and distribution of muscular work can be compared across a combination of external loads and ranges of motion, both factors that influence the change in energies. These data may provide strength and conditioning professionals insight into the relevant uses of these exercises and their variations. Further, quantification of the kinetics and kinematics provide an understanding of how work is generated.

MECHANICS OF JUMPING AND WEIGHTLIFTING

Vertical jumping is a multi-segment task that consists of two phases: propulsion and landing. The objective of the propulsive phase is to maximize the height of rise of the jumper's centre of mass. To accomplish this, individuals employ a characteristic pattern of muscular moments, starting proximally (i.e. hip extensors) and moving distally (towards the ankle plantar-flexors) (3, 4). This stereotypical pattern is required to maximize the kinetic energy of the musculoskeletal system to propel the body (5). Bobbert et al. (5) explains that to ensure maximal energy production, peak vertical velocity of the proximal and distal segments must be reached in sequence. This also guarantees that the monoarticular hip and knee extensors shorten over their full range, thus reaching their peak activation and producing a maximal amount of work before ground contact is lost (5). Overall, to create an optimal movement pattern during jumping, a specific timing, sequencing and muscle activation is required.

After maximum elevation of the center of mass, the body falls towards the ground resulting in a collision between the body and the ground. The impact or landing phase begins at the instant of contact. At this point, muscular work is performed to absorb the energy lost by the falling body and to reduce the velocity of the body to zero. A distal to proximal muscle effort and joint hierarchy is utilized to attenuate the impact forces applied to the body (3, 4). The initial muscles utilized to attenuate impact forces are the ankle plantar-flexors, followed by the knee and hip extensors. This sequence of muscular effort has been suggested to allow for greater energy absorption by the proximal musculature, which by design, are better suited to absorb the energies of impact (21). However, the joint and segment kinematics and kinetics are ultimately dependent on the landing technique employed.

A range of landing tasks from various heights has been studied in an attempt to understand how differences in task constraints influence the mechanics of landing (2-4, 10, 16, 21). Across landing techniques, there is little difference in ankle dorsiflexion range of motion reported at initial contact (4). However, ranges of knee and hip excursions have been determined across landing types (3, 4, 10). Increased stiffness of the lower extremity during drop landings has been found to increase knee extensor and ankle plantar-flexor torques, due to decreased joint excursions (3, 4). Higher ground reaction forces are also often observed with stiffer landings (21). With softer landings, hip and knee musculature absorb more energy, as a consequence of greater joint excursions, and lower ground reaction forces are observed (10, 21). Trunk position is also frequently reported because it influences hip muscle function through changes in the moment arm of the hip extensors (16). Landing with increased hip flexion has been shown to increase hip extensor torque as a result of greater hip excursion (10, 16). Most importantly, landing mechanics are dependent on the technique utilized, which will vary as a result of the task constraints.

Weightlifting tasks are different to landing from a jump, as weightlifting requires interaction with a barbell. However, both jump landing and the catch phase of weightlifting are eccentric activities, involving hip and knee flexion and ankle dorsiflexion. Weightlifting exercises such as the clean are frequently utilized in strength and conditioning training as a means of developing the ability to maximally and rapidly develop force (9). The ability to develop force rapidly has been associated with performance in other athletic tasks, including vertical jumping (13). The objective of the clean is to lift an external load from the ground to the shoulders. In order for heavy loads to be lifted, appropriate technique is required to create a coordinated multi-segment movement.

Similar to jumping, the clean consists of both propulsive and landing (catch) components. The clean exercise can be described by seven phases: 1) pre-lift 2) first pull 3) second knee bend 4) second pull 5) pull under the bar 6) amortization and 7) recovery (18) (Figure 1 – 2). Each phase involves distinct segment kinematics, kinetics and muscle activation patterns (18). The clean is an advantageous mode of training in strength and conditioning, as it requires rapid changes in direction. One of these changes in direction occurs in the transition from the fourth to fifth phase and another in the transition from the fifth to sixth phase. These transitions constitute the catch phase of the lift. Biomechanical analysis has reported that following the first pull, the hip reaches maximum extension before the knee and ankle, and the trunk is maximally extended during the pull under the bar phase (Figure 1 – 2) (8). Elite weightlifters are reported to land with knee flexion of ≈140° at initial contact and reach a deep squatting position (≈148°) as permitted by the large dorsiflexion motion of the leg (8, 18). No data on the joint kinetics are available for this portion of weightlifting tasks.

Figure 1 – 2: Clean exercise. A-B – first pull; B-C – second knee bend; C-D – second pull; D-F – pulling under and receiving barbell.

A comparison between the catch phase of weightlifting tasks and landing from a jump is valuable, as weightlifting exercises are often espoused for enhancing jumping performance (9, 13). To date, there is only one comparison between the catch phase of weightlifting and landing from a jump (7). Ground reaction forces were recorded for three jump landing activities including the vertical jump, drop landing (42 cm and 63 cm) and power clean (80% and 90% 1 RM). The results showed similar force – time curves across tasks where two impact peaks were observed in the first 150 ms, followed by a levelling off of the vertical ground reaction force. While similar force – time curves were observed, higher impact forces were found when landing from a jump (5.37N/kg) compared to catch phase of the power clean (1.47N/kg). The authors concluded that contrary to popular belief, when executed properly, weightlifting exercises impose less impact force than when landing from a jump. While this study provides valuable information pertaining to the impact forces generated during these tasks, no examination of the joint and segment kinematics and kinetics were considered.

Loaded and unloaded squat exercises, however, have been studied (6, 12) and as both landing from a jump and the catch phase of weightlifting involve at least a partial squat, the mechanics of squatting may be considered. In the squat position of the catch phase, to ensure that the barbell is maintained on the shoulders or locked overhead, an erect trunk posture is crucial. To afford this, forward displacement of the shank is needed, which consequently influences the joint kinetics across the lower extremity. Fry et al. (12) found that squatting with unrestricted leg rotation, greater loading of the knee extensors and a higher knee extensor NJM are achieved compared to squatting with restricted leg motion. Further, Bryanton et al. (6) investigated the effect of barbell load and squat depth on lower extremity kinetics. As squat depth increased, greater knee extensor relative muscular effort was observed. In contrast, ankle plantar-flexor relative muscular effort did not increase with increasing squat depth. These data indicate that the knee extensors are responsible for controlling the body's ascent and descent during squat tasks. These findings are also consistent with studies of jump landings where knee extensor NJM and the percentage work contribution at the knee are higher in landings with greater joint excursions (i.e. soft landings) (3, 10, 21). Based on these studies, it is expected that the highest knee extensor mechanical effort will be observed in tasks with large knee flexion angles. Alternately, when knee flexion is restricted, knee extensor mechanical effort should be lower, resulting in greater mechanical effort from other muscle groups.

The catch phase of weightlifting may provide a unique perspective on the role of impact force attenuation and the energetics of landing. While there is vast evidence on the relationship of the kinematics and kinetics to power production and work performed in the propulsive phase (11, 13, 14), there is a lack of research related to the catch phase. Research has found that the kinematics influence impulse and ground reaction force for variations of weightlifting exercises and therefore, the technique of the lift will determine how the body absorbs impact forces (15). Yet, no research has studied the distribution of joint work and how the joint and segment kinematics utilized during the catch phase influence the energetics. Given that the power clean involves a partial squat position whereas the clean requires full squatting motion, it is expected that the distribution of work performed at different joints will vary. Moreover, how this work is performed, specifically, the combination of NJM and joint excursions would also expect to change, depending on technique.

CONCLUSION

The pattern of energy absorption during high impact, eccentric activities has sparked interest from biomechanists. Conceptually, the work-energy theorem provides a foundation for understanding how the body absorbs energy. However, the main limitation of the point mass method underestimates the true mechanical energy of the musculoskeletal system (19). Thus, a more accurate estimate, using inverse dynamics techniques, affords the measurement of joint moments and excursions to determine the work performed by muscles. Previous research (3, 4, 10, 16) has demonstrated that various task constraints, affects the muscular effort and joint excursion, which in turn influences the distribution of work across the lower extremity. That being said, it is of interest to explore the distribution of work across a variety of landings. Weightlifting, an eccentric task that is modified by either an external load or variation in joint excursion, may provide a rare perspective on the distribution of work during landing. While there is an abundance of available research on the propulsive phase of weightlifting and jumping (5, 13, 14) a comparison of landing from a jump and the catch phase of weightlifting may yield an unrivaled analysis of the energetics of landing.

OBJECTIVE

The main objective of this research is to investigate the work performed by the lower extremity during high impact eccentric tasks. Specifically, the purpose is to examine how work performed is distributed across the hip, knee and ankle in weightlifting and jump landing tasks. If a difference in distribution is found, a secondary objective is to explore why there are differences in the distribution of work between tasks. To accomplish this, the kinematics and kinetics of each task will be examined.

HYPOTHESES

After exploring the literature (3, 4, 10, 16, 21), it is expected that differences will be found in the amount of work performed across the lower extremity during weightlifting and jump landing tasks. As a result of the externally applied load, it is hypothesized that more work will be performed at the knee, than the hip and ankle for the weightlifting tasks compared to the jump landing tasks. Moreover, the greater muscular work performed at the knee will be a consequence of a high knee extensor NJM or knee excursion or both.

SIGNIFICANCE

This research will contribute to our current understanding of the work performed and distribution of work at the hip, knee and ankle across four distinct landing tasks. Through kinematic and kinetic analysis, this study will explain how work is performed during landing and specifically, the role of the major lower extremity musculature during high impact eccentric activities. For sport coaches and strength and conditioning professionals, this research will determine which muscles and muscle groups are essential to absorbing impact forces generated during jumping and landing sports.

REFERENCES

1. Bernstein, NA. The Co-Ordination and Regulation of Movements. Oxford; Pergamon Press, 1967.

2. Bobbert, MF, Mackay, M, Schinkelshoek, D, Huijing, PA, and van Ingen Schenau, GJ. Biomechanical analysis of drop and countermovement jumps. *Eur J Appl Physiol* 54: 566-573, 1986.

3. Bobbert, MF, Huijing, PA, and Van Ingen Schenau, GJ. Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Med Sci Sports Exerc* 19: 332-338, 1987.

4. Bobbert, MF, Huijing, PA, and Van Ingen Schenau, GJ. Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Med Sci Sports Exerc* 19: 339-346, 1987.

5. Bobbert, MF, and Van Ingen Schenau, GJ. Coordination in vertical jumping. *J Biomech* 21: 249-262, 1988.

6. Bryanton, MA, Kennedy, MD, Carey, JP, and Chiu, LZF. Effect of Squat Depth and Barbell Load on Relative Muscular Effort in Squatting. *J Strength Cond Res* In Press.

7. Burkhardt, E, Barton, B, and Garhammer, J. Maximal impact and propulsion forces during jumping and explosive lifting exercises *J Appl Sport Sci Res* 4: 107 - 117, 1990.

8. Campos, J, Poletaev, P, Cuesta, A, Pablos, C, and Carratalá, V. Kinematical analysis of the snatch in elite male junior weightlifters of different weight categories. *J Strength Cond Res* 20: 843-850, 2006.

9. Chiu, LZF, and Schilling, BK. A primer on weightlifting: From sport to sports training. *Strength Cond J* 27: 42-48, 2005.

10. DeVita, P, and Skelly, WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc* 24: 108-115, 1992.

11. Enoka, RM. Load- and skill-related changes in segmental contributions to a weightlifting movement. *Med Sci Sports Exerc* 20: 178-187, 1988.

12. Fry, AC, Smith, JC, and Schilling, BK. Effect of Knee Position on Hip and Knee Torques during the Barbell Squat. *J Strength Cond Res* 17: 629-633, 2003.

13. Garhammer, J, and Gregor, R. Propulsion forces as a function of intensity for weightlifting and vertical jumping. *J Appl Sport Sci Res* 6: 129, 1992.

14. Garhammer, J. A review of power output studies of olympic and powerlifting: Methodology, performance prediction, and evaluation tests. *J Strength Cond Res* 7: 76, 1993.

15. Jensen, RL, and Ebben, WP. Impulses and ground reaction forces at progressive intensities of weightlifting variations. In: Proceedings of the XX Int Symp Biomech Sports 2002: 222-225.

16. Kulas, A, Zalewski, P, Hortobagyi, T, and DeVita, P. Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings. *J Biomech* : 180-185, 2008.

17. Rao, G, Amarantini, D, and Berton, E. Influence of additional load on the moments of agonist and antagonist muscle groups at the knee joint during closed chain exercise. *J Electromyogr Kinesiol* 19: 459-466, 2009.

18. Reiman, MP, Escamilla, RF, and Chiu, LZF. Applied biomechanics of common weight training exercises. In: Athletic and Sport Issues in Musculoskeletal Rehabilitation. Magee, DJ, Manske, RC, Zachazewski, JE and Quillen, WS, eds. Elsevier, 2011.

19. Robertson, DGE, Caldwell, GE, Hamill, J, Kamen, G, and Wittlesey, SM. Research Methods in Biomechanics. Ontario; Human Kinetics, 2004.

20. Robertson, DGE, and Winter, DA. Mechanical energy generation, absorption and transfer amongst segments during walking. *J Biomech* 13: 845-854, 1980.

21. Zhang, S, Bates, BT, and Dufek, JS. Contributions of lower extremity joints to energy dissipation during landing. *Med Sci Sports Exerc* 32: 812-819, 2000.

CHAPTER II

INTRODUCTION

Weightlifting and jumping are tasks with similar biomechanical characteristics. Both tasks involve propulsive and landing phases. The goal of the propulsive phase is to generate a coordinated mechanical output across the lower extremity to optimize the vertical rise of either the jumper's centre of mass or the barbell. The objective of the landing or catch phase, by contrast, is to create a synchronized pattern of eccentric muscular effort to attenuate the forces present at impact and to stop the falling body or barbell. To date, the majority of research in jumping and weightlifting has focused on the mechanics of the propulsive phase (4, 5, 10, 12, 13), while less emphasis has been placed on understanding landing mechanics.

After reaching their apex, the jumper or barbell fall towards the ground and potential energy is lost and kinetic energy is gained. Following impact, more potential energy is lost until the body stops descending. Muscular work must be performed to absorb this energy and reduce the velocity of the body to zero post-impact. Although there is an abundance of research related to the energetics of jumping to improve performance (5, 12), few studies (3, 8, 15, 22) have quantified the energetics and distribution of muscular work during landing. Further, the energetics of the catch phase of weightlifting have not been studied.

Previous investigations have determined that, due to various constraints of landing tasks, the distribution of muscular work across the lower extremity can vary (3, 8, 15, 22). Bobbert et al. (3) found landing with increased ankle dorsiflexion, and knee and hip flexion were associated with higher peak net joint moments (NJM). DeVita et al. (8) compared the distribution of muscular work performed across the lower extremity during soft and stiff landings. Soft and stiff landings were characterized as having greater or less than 90 degrees of knee flexion, respectively. For stiff landings, more work was performed at the ankle, while during soft landings, more work was performed at the knee. Zhang et al. (22) noted differences in work performed and the distribution of work across a range of landing techniques and heights. They reported similar results to DeVita (8), where the ankle plantar-flexors performed more work in the stiff landings. In contrast to DeVita (8), they also observed greater work performed at the hip for in soft landings. Increases in landing height required more work to be performed at the ankle and hip. Further, manipulation of trunk load and position has been demonstrated to influence how work is distributed across the hip, knee and ankle (15). When landing from a jump with the trunk in a more extended position, the amount of work performed at the hip decreases while the amount of work at the knee and ankle increases (15). Taken together, these studies demonstrate that the constraints imposed during different landings influences the work performed across the lower extremity.

The catch phase of weightlifting and landing from a jump have distinctive constraints that may provide novel information related to the energetics of landing. Weightlifting exercises are different from landing from a jump because of the interaction between the lifter and the barbell. It is also possible to modify joint ranges of motion to perform variations of weightlifting exercises, where the barbell can be caught in a full or partial squat, for example a clean versus a power clean. Therefore, studying weightlifting task variations can provide valuable information relating to how the lower extremity performs work when task constraints such as a heavy implement and range of motion are present. By comparing weightlifting and jump landing tasks, it may be possible to identify generalized characteristics of landing as well as characteristics that are task-specific. Thus, the primary objective of this study was to determine the work performed and how it was distributed across the hip, knee and ankle during weightlifting and jump landing tasks. A secondary objective was to explore how joint and segment kinematics and kinetics related to differences in the distribution of work during these tasks.

METHODS

Experimental Approach to the Problem

This study used a cross-sectional design to compare the biomechanics of two jump landing and two weightlifting tasks. The weightlifting tasks performed were the clean and power clean and the jump landing tasks completed were the block countermovement jump and drop landing. All tasks were performed in a motion analysis laboratory. For the primary objective, the total work performed at the hip, knee and ankle, and the percentage of total work performed at each of these joint was determined and compared across the four tasks. For the secondary objective, joint and segment kinematics and kinetics were determined and compared across tasks.

Participants

Ten women were recruited to participate in this investigation. Subjects provided written informed consent as approved by a University of Alberta Research Ethics Board (Pro00024475) and completed a physical activity questionnaire. All subjects had been taught to perform the clean and power clean by a Coaching Association of Canada Level 1 certified weightlifting coach. Further, they had a minimum of 6 months experience performing these exercises in their strength and conditioning program under the supervision of the coach. Participant characteristics are presented in Table 2 – 1.

Table 2 – 1: Participant characteristics.

	Mean ± *SD*	Range
Height (m)	1.79 ± 0.07	1.67 – 1.93
Body mass (kg)	71.20 ± 8.99	59.70 – 91.40
Maximal vertical jump (m)	0.46 ± 0.04	0.41 – 0.53
One Repetition Maximum (kg)	57.00 ± 5.83	48.00 – 66.00

Procedures

Participants completed two sessions, spaced approximately one week apart. During the first session, the subjects' maximal block jump height was determined. The block jump involved a brief countermovement, followed by rapid extension at the hip, knee and ankle while reaching upwards with the arms. The difference between standing height and maximal jump height was used to determine the participant's height for the drop landing trials. The box height was equivalent to the participant's maximal jump height. Our prior research suggests familiarization practice is required to achieve stable performance in landing tasks and although a novel task, stable performance in drop landings is achieved with less practice than jump landings (16). The participants viewed an instructional video demonstrating proper landing technique. The participants were instructed to:

- Land with feet symmetrical
- Land with knees and ankles bent
- Land with feet flat
- Land with the body upright; avoid leaning forward
- Absorb the landing using muscle tension

The participants practiced five block jumps and five drop landing trials following the instructional video. For the drop landings, the foot leading off was decided by the participant and was kept the same for each trial. Arm motion was not constrained. Practice for the power clean and clean was not required as these tasks were performed regularly in training and instruction on technique had previously been provided.

In the second session, participants performed jumping (Figure 2 – 1), drop landing (Figure 2 – 2) and weightlifting (Figure 2 – 3; Figure 2 – 4) trials with performance recorded by a 3D motion capture system. Participants completed a brief warm up consisting of two sets of five body weight squats. Subsequent to the warm-up, participants performed four repetitions each of maximal-effort block jumps and drop landings from the predetermined box height. Previous research indicates repeatable results with four repetitions of jump landing tasks (16). Following the jumping and landing trials, the power clean and clean exercises were performed at 80% of the participant's one repetition maximum clean (as determined from the athlete's training journal). Three sets of two repetitions were performed for each weightlifting exercise. Sets of power cleans and cleans were alternated to prevent an ordering effect. Rest was provided ad libitum between repetitions and sets.

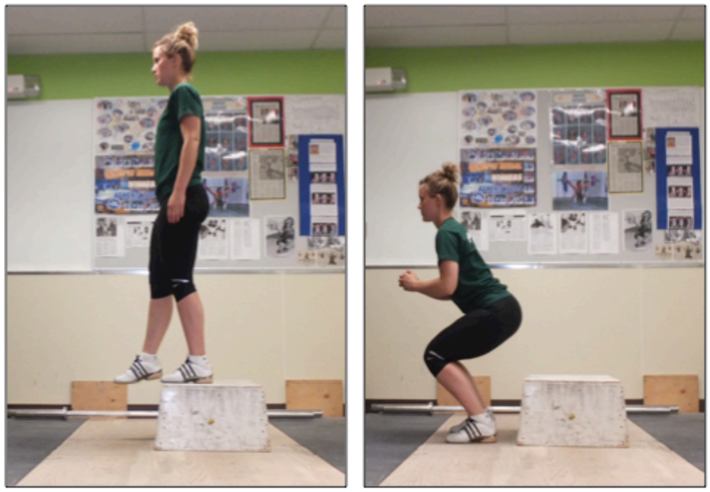


Figure 2 – 1: Drop landing task.

Figure 2 – 2: Block jump task.

Figure 2 – 3: Power clean task.

Figure 2 – 4: Clean task.

Motion Analysis

Marker trajectories were recorded using a nine optoelectronic camera (ProReflex MCU240; Qualisys, Gothenburg, Sweden) motion capture system sampling at 120Hz. To track segments, a six degree-of-freedom retro-reflective marker set was placed on the participants' lower extremities (see Bryanton et al. (6) for details). This marker set consisted of calibration and tracking markers. Calibration markers were utilized during static trials to define the proximal and distal ends of segments. Calibration markers were placed on the foot (1st and 5th metatarsal heads), ankle (medial and lateral malleoli), knee (medial and lateral epicondyles) and hip (greater trochanters) (Figure 2 – 5). Clusters of markers fixed on a rigid plastic plate were used for tracking the thigh, leg and foot. To define and track the pelvis, markers were placed on the left and right iliac crests and L5/S1. The participant's lower extremity was modeled as seven rigid segments – left and right feet, left and right leg, left and right thighs, and pelvis. Two AMTI force platforms (OR6-6; AMTI, Watertown, MA) sampling at 1200Hz were used to collect ground reaction force data. Participants were instructed to place one foot on each force platform during jumping, drop landing and weightlifting tasks.

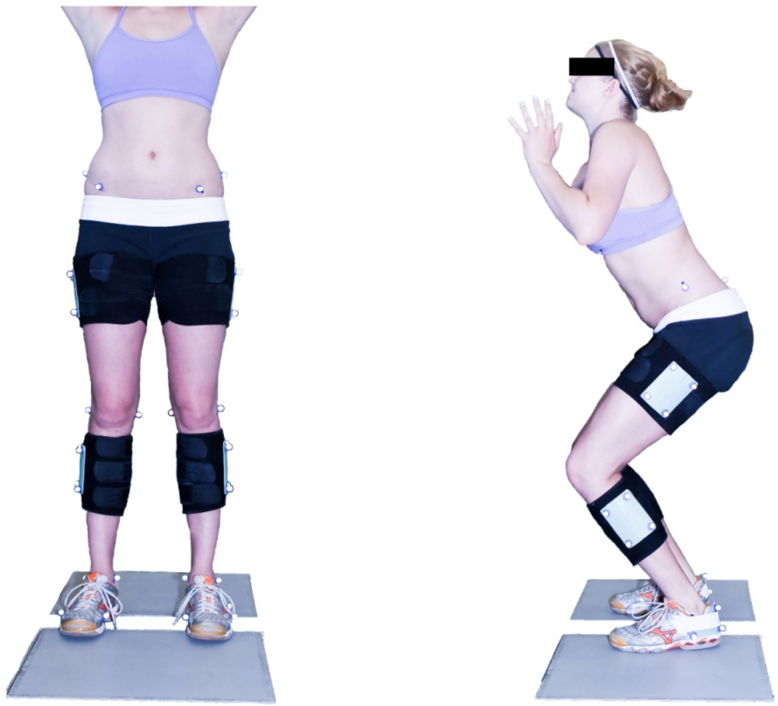
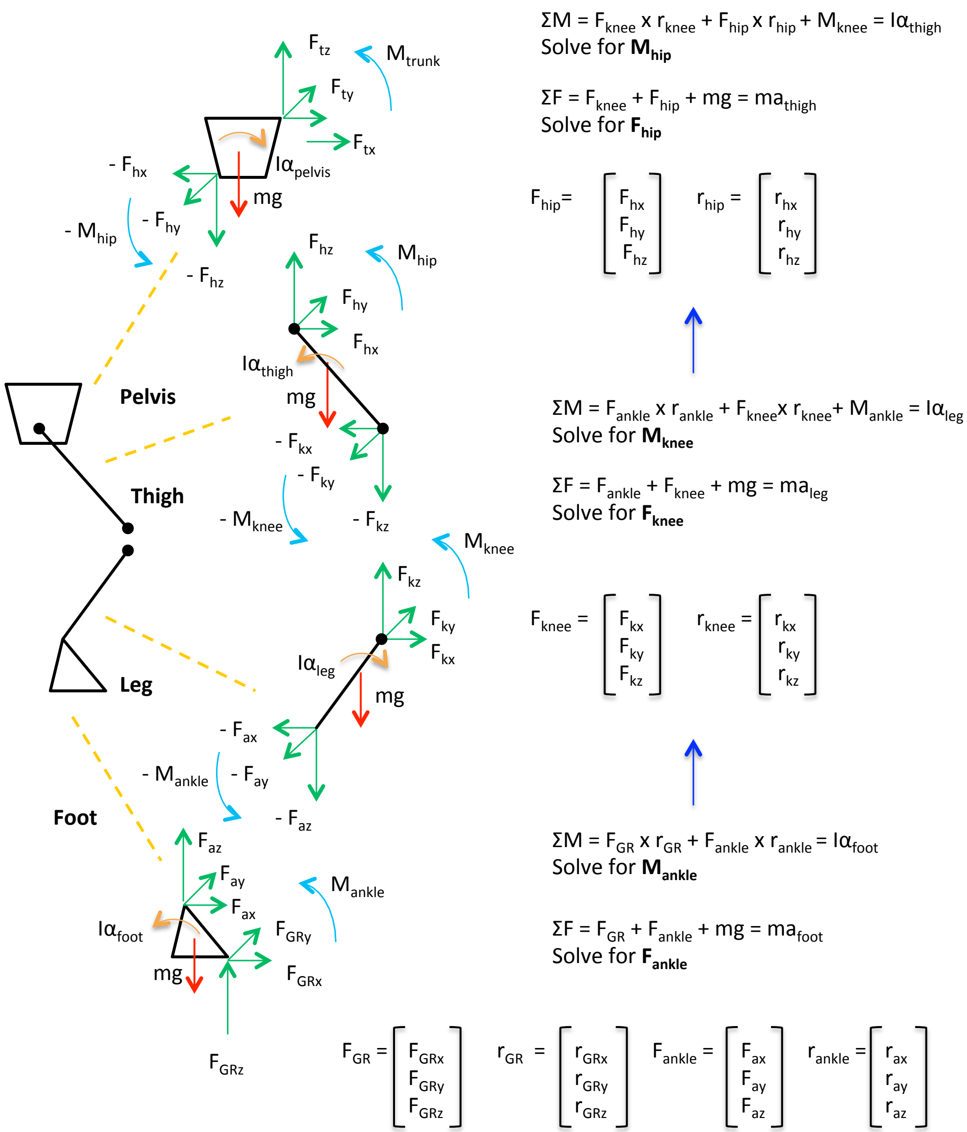


Figure 2 – 5: Calibration and tracking marker sets.

Data Processing and Analysis

Reflective marker data were processed in Visual 3D software (Version 4.82; C-Motion, Germantown, MD) to determine segment and joint kinematics. Marker and force platform data were filtered using a low-pass fourth order recursive Butterworth with a 10 Hz cut-off frequency. Derivatives were calculated using the finite differences technique. A ZYX Cardan sequence relative to the laboratory frame was used to determine rotations of the foot, leg, thigh and pelvis segments. The ankle, knee and hip joints were defined as the relative motion of the proximal segment on the distal segment. Joint angles and velocity were determined using an XYZ Cardan sequence. Inverse dynamics procedures (Figure 2 – 6) were used to calculate the NJM at the ankle, knee and hip with moments expressed in the coordinate system of the distal segment. Segments were modelled as conical frusta. Proximal and distal markers on segments were used to define segment length and the radii of each end of the frusta. Segment mass was determined as a percentage of total body mass using Dempster's data (21).



*Moments are solved about the COM

Figure 2 – 6: Free body diagram for inverse dynamics calculations.

Joint power was calculated as the dot product of NJM and joint angular velocity. Work was determined as the time integral of the joint power data between two discrete points of interest. These points of interest were 1 frame before ground contact and at peak knee flexion. These points were chosen to represent the start and end of the landing phase. The total work performed was the sum of the absolute work at the hip, knee and ankle. Percentage contribution from each joint was also determined for each task (9). Kinematic data were averaged between right and left limbs following visual verification that the limbs were similar. Kinetic data were summed between right and left limb, and normalized to body mass. The kinematic and kinetic data of each task performed were averaged across all trials performed.

Statistical Analysis

To examine if differences existed between tasks for the total work performed, a one-way analysis of variance (ANOVA) with repeated measures was used. To determine if the percentage contribution of work performed at the ankle, knee and hip differed across tasks, a repeated measures multivariate ANOVA was used, with work performed at the ankle, knee and hip as multivariate levels. Repeated measures multivariate ANOVA was used to examine differences between tasks for: 1) joint and segment angles at initial and peak knee flexion, 2) total joint excursion and 3) NJM at peak knee flexion. Tukey's Honestly Significant Difference test was used for post hoc comparisons.

For all statistical tests, alpha was set *a priori* ($\alpha=0.05$). Statistical tests were performed in SPSS (version 11.0; SPSS Inc., Chicago, USA).

RESULTS

The total work performed by the lower extremity was different between tasks ($p<0.001$; Figure 2 – 7). The work performed in the clean and drop landing were not different ($p=0.10$) which was more than the work performed when landing from the block jump ($p<0.05$). The work performed in the power clean was significantly less than the other three tasks ($p<0.05$). A significant main effect was found for the percentage contribution of work performed at the hip, knee and ankle ($p<0.001$; Figure 2 – 8). Univariate ANOVAs indicated significant main effects of task at the ankle ($p<0.001$) and knee ($p<0.001$) but not at the hip ($p=0.20$). The percentage contribution of work performed at the ankle was greatest for the jump landing tasks. The percentage contribution of work performed at the knee was greatest for the weightlifting tasks.

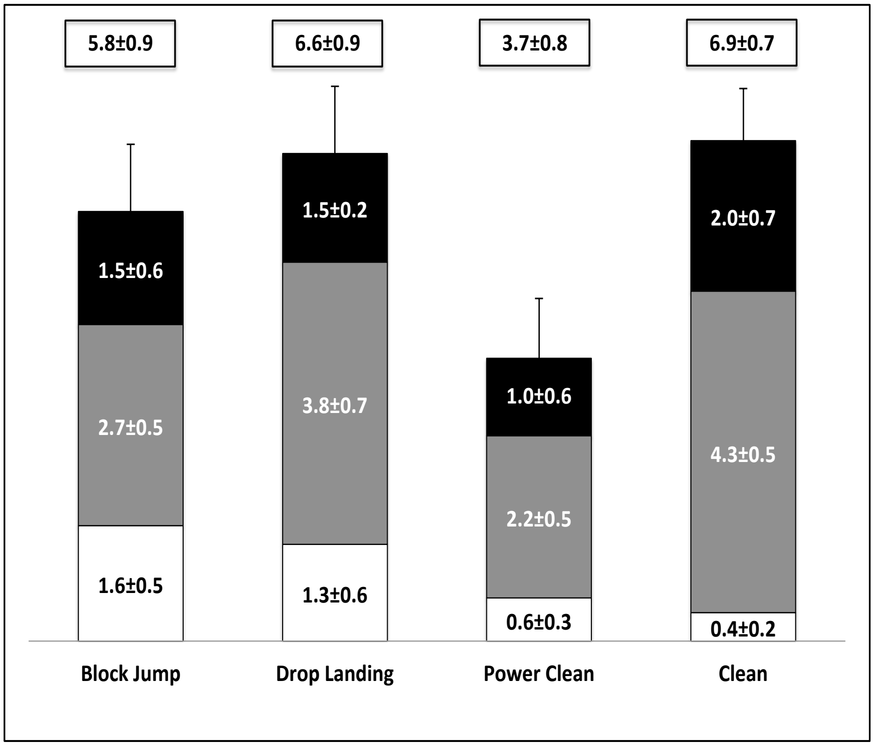


Figure 2 – 7: Work ($J \cdot kg^{-1}$) performed at the hip (black), knee (grey), ankle (white) and sum (box).

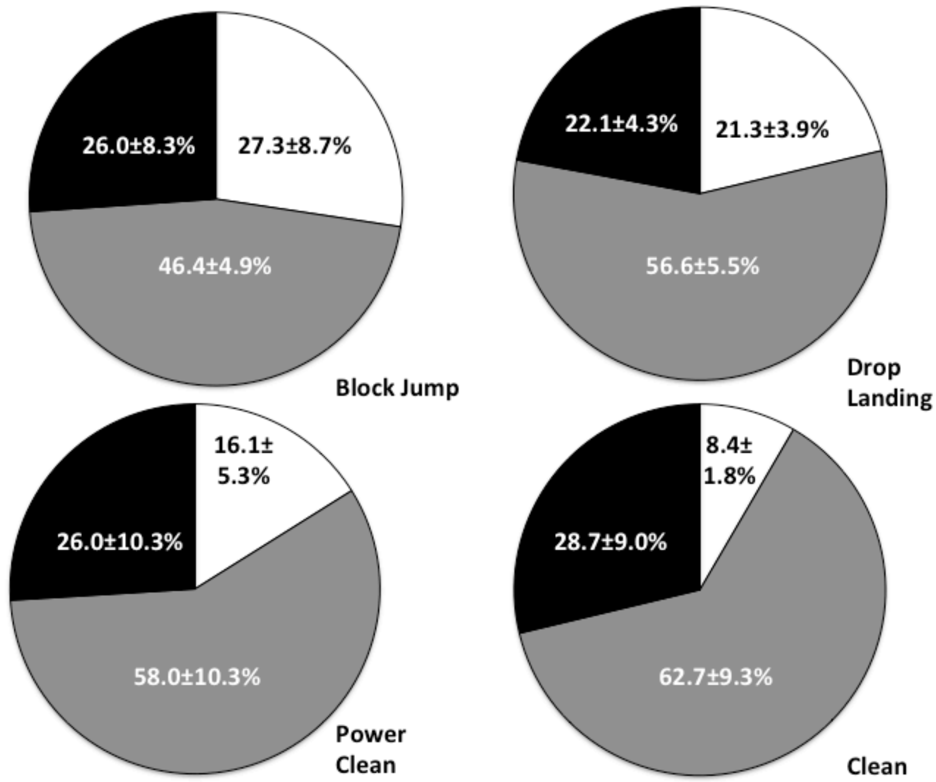


Figure 2 – 8: Percentage contribution of work performed at the hip (black), knee (grey) and ankle (white) to total lower extremity work.

The large percentage contribution of ankle work in the block jump and drop landing was a result of large ankle excursions (Table 2 – 2). In these tasks, the foot was more plantar-flexed when contacting the ground than in the power clean and clean (p<0.05; Figure 2 – 9). At peak knee flexion, the ankle angle was not different between the block jump, drop landing and power clean (p>0.05; Figure 2 – 10). Ankle angle at peak knee flexion was greatest for the clean (p<0.05). Ankle plantar-flexor NJM was similar for the block jump and drop landing (p=0.95; Table 2 – 3), which was lower than in the power clean and clean

($p<0.05$). There was no difference in ankle plantar-flexor NJM between the power clean and clean ($p=0.97$).

Table 2 – 2: Joint excursions (°) from initial contact to peak knee flexion. Positive values are ankle dorsiflexion and hip flexion. Mean ± SD.

Joint	Task			
	Block Jump	Drop Landing	Clean	Power Clean
Ankle	60 ± 13	54 ± 7	29 ± 13	27 ± 10
Knee	-78 ± 12	-86 ± 12	-86 ± 17	-41 ± 18
Hip	62 ± 11	62 ± 11	66 ± 16	34 ± 19

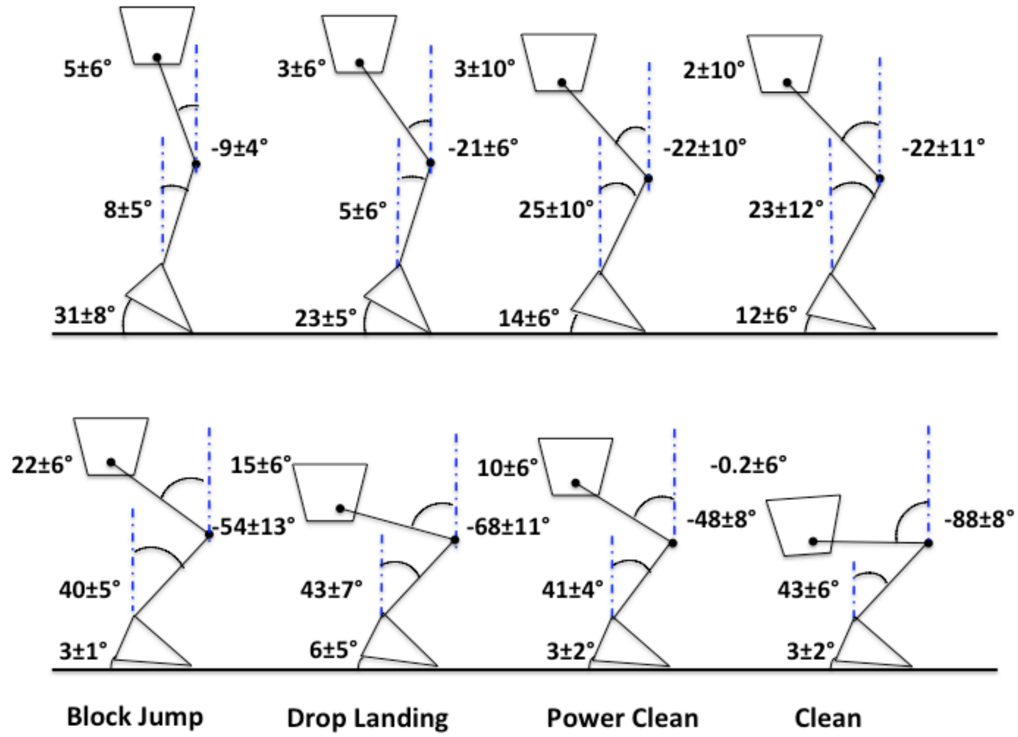


Figure 2 – 9: Pelvis, thigh, shank and foot segment angles (°) at initial contact (top) and peak knee flexion (bottom). Mean ± SD.

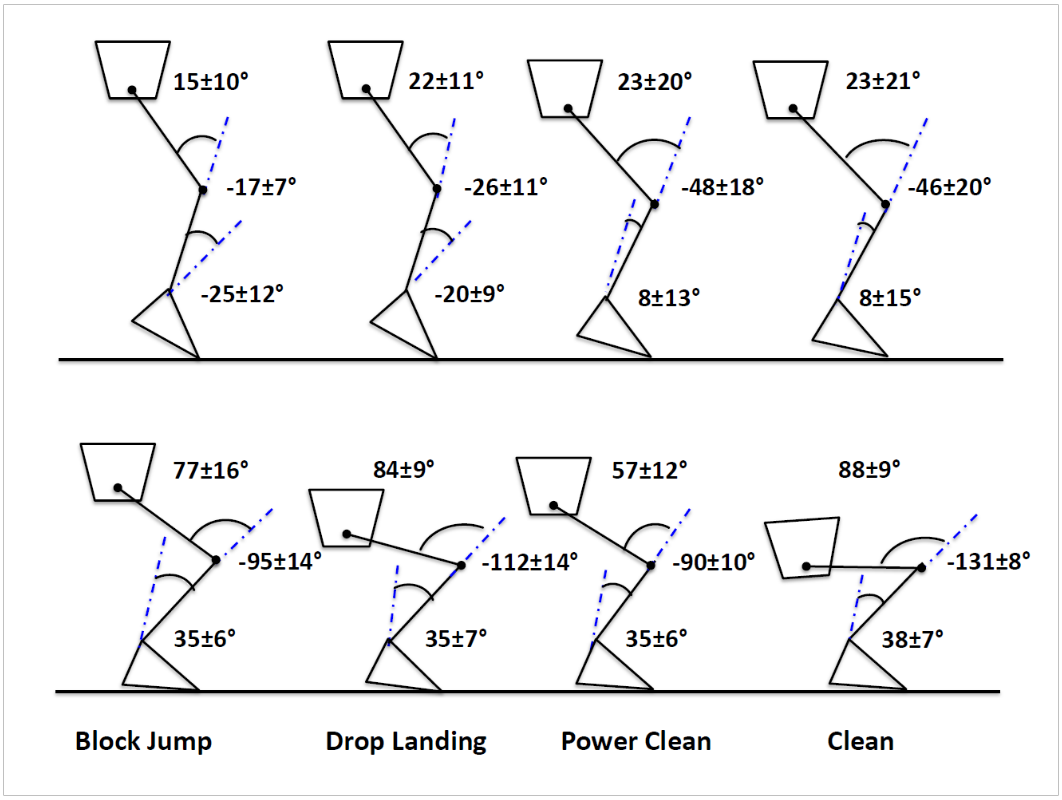


Figure 2 – 10: Hip, knee and ankle joint angles (°) at initial contact (top) and peak knee flexion (bottom). Mean ± SD.

Table 2 – 3: Hip, knee and ankle net joint moments ($N \cdot m \cdot kg^{-1}$) at peak knee flexion. Positive values indicate ankle plantar-flexor, knee flexor and hip extensor moments. Mean ± SD.

Joint	Task			
	Block Jump	Drop Landing	Clean	Power Clean
Ankle	1.5 ± 0.4	1.5 ± 0.4	2.0 ± 0.4	1.9 ± 0.4
Knee	-2.9 ± 0.8	-2.9 ± 1.0	-4.5 ± 1.3	-3.7 ± 0.7
Hip	2.5 ± 0.5	2.1 ± 0.6	3.6 ± 0.5	2.3 ± 0.7

The small percentage contribution from knee work to the block jump was due in part to the large percentage contribution of ankle work, but also to a small knee extensor NJM. Knee extensor NJM was lower in the block jump than the power clean (p=0.04) and clean (p<0.001). Percentage contribution of knee work was not different between the power clean and drop landing. However, how work was performed was different between these tasks, with greater knee excursion in the drop landing (p<0.001) versus higher knee extensor NJM in the power clean (p=0.05). The large percentage contribution of work performed at the knee in the clean was the result of greater knee extensor NJM (p<0.05) and knee angular excursion (p<0.05) than the other tasks.

Additional differences in kinematics were observed between tasks at initial contact and peak knee flexion. Most notably, the angle of the foot and leg at initial contact was found to differ across tasks. The jump landing tasks had greater foot plantar-flexion and less leg dorsiflexion when compared to the weightlifting tasks ($p<0.05$). No differences across tasks for foot and leg angle were found at peak knee flexion ($p>0.05$; Figure 2 – 9). At initial contact, the ankle was in plantar-flexion for the jump landing tasks, whereas for the weightlifting tasks, the ankle was in dorsiflexion ($p<0.05$; Figure 2 – 10). Greater knee flexion angles were observed for the weightlifting tasks ($p<0.05$). At peak knee flexion, the clean showed the greatest range of motion across the lower extremity ($p<0.05$). The power clean, however, had the least range of motion at the knee and hip when compared to the other tasks ($p<0.05$).

DISCUSSION

The major finding of this investigation was that the contribution of work performed at the ankle and knee varied across landing types. Moreover, two distinct lower extremity postures were noted at each of the points of interest – initial contact and peak knee flexion – that explain the difference in work performed at these joints. At initial contact, the foot was plantar-flexed and the leg was not rotated forward (i.e. vertical) in the block jump and drop landing. In contrast, the foot was neutral and the leg was rotated forward at initial contact in the power clean and clean. The foot and leg angles were not significantly different between tasks at peak knee flexion. However, at peak knee flexion, significantly greater ankle dorsiflexion and knee flexion were observed in the clean. The large foot and leg rotations in the jump landing tasks were accompanied by greater work performed at the ankle when compared to the weightlifting tasks. Large amounts of work performed at the ankle in these tasks are consistent with the stiff-landing technique described in the literature (3, 8).

However, stiff-landings have also been described as having less knee flexion than soft-landings (8). While ankle work was large in both jump landing tasks, the block jump had less peak knee flexion than the drop landing. Similarly, the power clean had less peak knee flexion than the other tasks. The largest amount of work performed at the knee due to large knee excursion occurred in the drop landing and clean, with the least knee work observed in the block jump and power clean. The greater ankle work and lesser knee work in the block jump are consistent with previously described stiff-landings (3, 8). The small ankle work and large knee work in the clean are characteristics of soft-landings (8). The work performed in the drop landings and power cleans, however, do not allow these tasks to be characterized by the soft- and stiff-landing conventions. In the power clean, the work at the ankle and knee, as well as the peak knee flexion angle are small. Therefore neither soft- or stiff-landing descriptions can be used to characterize this task. The drop landing had large amounts of work performed at the ankle and knee, in addition to a large peak knee flexion angle. The mechanics of the drop landing are particularly significant as this task demonstrated features of both soft- and stiff-landings.

Thus the distinction between soft- and stiff-landings does not appear to be supported when muscular work performed is considered in a variety of tasks. Rather, our data suggest that the ankle plantar-flexors and knee extensors have unique roles in landing tasks, which provides a more accurate description of various landing techniques. The role of the ankle plantar-flexors is to control motion of the foot and leg to absorb the energies present at impact. The amount of work performed at the ankle is therefore determined before impact, based on whether the foot is plantar-flexed and the leg is rotated forward. The pre-impact posture consequently influences how much leg rotation is required post-impact. Since there is greater foot plantarflexion and less leg rotation in the jump landing tasks, more rotation is required to descend into a squat position. The weightlifting tasks, however, have less foot rotation and more leg forward rotation, and thus, there is a greater tendency for the leg to continue rotating forward, decreasing the need for the ankle plantarflexors to perform work.

The function of the knee extensors is to absorb energies to control motion of the thigh, which determines the depth of squat attained. It is important to consider that, regardless of the task, the joint contributing the most work in landing is the knee, which concurs with data from Zhang et al. (22). Even in the block jump, which had the highest contribution of ankle work (27%), the knee contributed 46% of the total lower extremity work performed. In addition to the high knee work contribution, knee extensor NJM was also large for each task. Knee extensor NJM ranged from 2.9 $N\cdot m\cdot kg^{-1}$ in the block jump to 4.5 $N.m.kg^{-1}$ in the clean. For comparison, knee extensor NJM of 2.4 $N\cdot m\cdot kg^{-1}$ for a moderately challenging (5RM) front squat exercise has been reported (1). Thus, compared to a squat exercise, it would appear that the knee extensors contribute to a greater extent to the work performed when landing from a jump.

The role of the knee extensors for controlling squat depth has also been reported for other tasks. Research from our laboratory has found that knee extensor NJM and relative muscular effort increase with squat depth (6). In contrast, squat depth has no effect on ankle plantar-flexor NJM and relative muscular effort. When landing from a jump, individuals with anterior cruciate ligament (ACL) deficient knees have decreased knee extensor NJM, which is compensated for by increased hip extensor NJM and forward trunk lean (17, 20). Individuals with ACL injury are known to have knee extensor strength and activation deficits (17-20). Moreover, Salem et al. reported decreased knee extensor and increased hip extensor NJM in squat exercise in ACL injured individuals. Taken together, these data highlight the importance of the knee extensors for controlling the lowering of the body into a squat position across a variety of tasks.

Development of knee extensor strength is therefore important in individuals performing squatting and landing tasks. Each of the landing tasks studied in this investigation have been recommended for strengthening the lower extremity, however, the effectiveness of each task varies (2, 3, 7). Our data may be used to identify which tasks may be appropriate for strengthening the knee extensors. The clean and drop landing required large amounts of work to be performed by the knee extensors, which suggests these tasks, would be effective. Further, the clean and drop landing required the most knee flexion, thus utilizing the knee extensor through the range of motion where they are weakest due to the decreased moment arm (6). However, the knee extensor NJM was lower in the drop landing than the power clean and clean. The NJM is an estimate of the force required by the knee extensor muscles. Therefore, larger forces are required to activate high-threshold motor units and elicit an optimal strengthening effect (14). The large knee extensor NJM in the power clean and clean indicate weightlifting exercises are most appropriate for strengthening the knee extensors. Altogether, the clean would appear to be the most effective of all the exercises as it has large knee flexion angles, greater knee extensor work performed and knee extensor NJM than the other tasks.

The value of the clean for strengthening the knee extensors, which require a deep squat, is supported by Bryanton et al. (6) and Hartmann et al. (11). The knee extensor muscle force as a percentage of maximum muscle force increases from a parallel to a deep squat (6). As greater effort is required with a deeper squat position, it can be suggested that the deep squat exercise is more effective for developing knee extensor strength than partial squats (11). It should also be considered that in the clean exercise, after the barbell is caught, the concentric portion of the squat is performed to ascend following peak knee flexion, requiring further activation of the knee extensors.

While this study provides valuable information related to the absorption of energy across four landing tasks, understanding the energetics of landing activities requires additional investigation. In the present study only one barbell load and one landing height were studied. How increasing barbell load or landing height influences the energetics of landing is not known. We have previously found that increasing drop landing height requires greater knee flexion, however, we did not study the NJMs or work performed. Additionally, we have found increasing barbell load from 50 – 90% 1 RM in the squat exercise has little effect on knee extensor muscle effort, but increases ankle plantar-flexor and hip extensor muscular effort (6). Thus, specific task constraints, such as barbell load or landing height, may uniquely influence landing energetics.

In summary, this research provides information pertaining to the roles of the ankle plantar-flexors and knee extensors to performing work across a variety of landing tasks. Ankle work is determined by the posture of the foot and leg at impact. The majority of work performed in all tasks occurred at the knee. Greater knee work was found for tasks with high peak knee flexion angles. Although large amounts of work were performed in drop landings and cleans, only the latter task (as well as the power clean) had high knee extensor NJM. The knee extensor NJM required in the clean and power clean indicate these weightlifting tasks may be important for developing knee extensor strength in the context of landing performance.

PRACTICAL APPLICATIONS

Weightlifting tasks have been promoted for developing muscular fitness for sport tasks such as jumping. Our research highlights an important, but often overlooked aspect of sport performance – landing. Landing tasks require muscular efforts to absorb energies from the falling body. Similarly, large muscular efforts are required in the clean and power clean to absorb energies from the falling lifter-barbell system. The landing phase of jumping and the catch phase of weightlifting tasks share similar mechanical characteristics, including foot and leg posture at peak knee flexion and large amounts of work performed at the knee to control the descent into a squat position. The large knee extensor NJM and knee flexion range of motion in the clean suggest this exercise has value for developing the strength required for absorbing energies involved in landing tasks. The clean, which requires a deep squat in the catch phase, should therefore be employed in the training of athletes involved in jumping and landing.

REFERENCES

1. Bobbert, MF, Mackay, M, Schinkelshoek, D, Huijing, PA, and van Ingen Schenau, GJ. Biomechanical analysis of drop and countermovement jumps. *Eur J Appl Physiol* 54: 566-573, 1986.

2. Bobbert, MF, Huijing, PA, and Van Ingen Schenau, GJ. Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Med Sci Sports Exerc* 19: 332-338, 1987.

3. Bobbert, MF, Huijing, PA, and Van Ingen Schenau, GJ. Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Med Sci Sports Exerc* 19: 339-346, 1987.

4. Bobbert, MF, and Van Ingen Schenau, GJ. Coordination in vertical jumping. *J Biomech* 21: 249-262, 1988.

5. Bosco, C, Ito, A, and Komi, PV. Neuromuscular function and mechanical efficiency of human leg extensor muscles during jumping exercises. *Acta Physiol Scand* 114: 543-550, 1982.

6. Bryanton, MA, Kennedy, MD, Carey, JP, and Chiu, LZF. Effect of Squat Depth and Barbell Load on Relative Muscular Effort in Squatting. *J Strength Cond Res* In Press.

7. Chiu, LZF, and Schilling, BK. A primer on weightlifting: From sport to sports training. *Strength Cond J* 27: 42-48, 2005.

8. DeVita, P, and Skelly, WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc* 24: 108-115, 1992.

9. Flanagan, SP, and Salem, GJ. The Validity of Summing Lower Extremity Individual Joint Kinetic Measures. *J Appl Biomech* 21: 181-188, 2005.

10. Garhammer, J. A review of power output studies of olympic and powerlifting: Methodology, performance prediction, and evaluation tests. *J Strength Cond Res* 7: 76, 1993.

11. Hartmann, H, Wirth, KPDD, Klusemann, MMA, Dalic, J, Matuschek, C, and Schmidtbleicher, DPDhc. Influence of squatting depth on jumping performance. *J Strength Cond Res* In Press.

12. Hubley, CL, and Wells, RP. A work-energy approach to determine individual joint contributions to vertical jump performance. *Eur J Appl Physiol Occup Phys* 50: 247-254, 1983.

13. Kipp, K, Redden, J, Sabick, MB, and Harris, C. Weightlifting Performance Is Related to Kinematic and Kinetic Patterns of the Hip and Knee Joints. *J Strength Cond Res* 26: 1838-1844, 2012.

14. Kukulka, CG, and Clamann, HP. Comparisons of the recruitment and discharge properties of motor units in human brachial biceps and adductor pollicis during isometric contractions. *Brain Res* 219: 45-55, 1981.

15. Kulas, A, Zalewski, P, Hortobagyi, T, and DeVita, P. Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings. *J Biomech*180-185, 2008.

16. Moolyk, AN, and Chiu, LZF. Instruction and multiple practice sessions affect landing mechanics. *Hum Movement Sci* In Review.

17. Oberländer, KD, Brüggemann, G-, Höher, J, and Karamanidis, K. Reduced knee joint moment in ACL deficient patients at a cost of dynamic stability during landing. *J Biomech* 45: 1387-1392, 2012.

18. Palmieri-Smith, RM, Kreinbrink, J, Ashton-Miller, JA, and Wojtys, EM. Quadriceps inhibition induced by an experimental knee joint effusion affects knee joint mechanics during a single-legged drop landing. *Am J Sport Med* 35: 1269-1275, 2007.

19. Palmieri-Smith, RM, Thomas, AC, and Wojtys, EM. Maximizing Quadriceps Strength After ACL Reconstruction. *Clin J Sports Med* 27: 405-424, 2008.

20. Salem, GJ, Salinas, R, and Harding, FV. Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil* 84: 1211-1216, 2003.

21. Winter, RA. Biomechanics and Motor Control of Human Movement: Second Edition. Toronto; John Wiley & Sons, Inc., 1990.

22. Zhang, S, Bates, BT, and Dufek, JS. Contributions of lower extremity joints to energy dissipation during landing. *Med Sci Sports Exerc* 32: 812-819, 2000.

CHAPTER III

GENERAL DISCUSSION

This research has demonstrated that the pattern of muscular work across four landing tasks varies. The most significant difference between tasks was the work performed at the ankle and knee, which has previously been found by others (4, 13, 25, 36). In the literature, landings have typically been characterized as soft or stiff, and these landing types are reported to have differences in the work performed at the ankle and knee (4, 13). Bobbert et al. (4) described the bounce drop jump, which has minimal knee flexion, as a stiff-landing technique and the countermovement drop jump, which has greater knee flexion, as a soft-landing technique. The stiff-landing technique had greater ankle work whereas the soft-landing had greater knee work. DeVita and colleagues (13, 25) similarly classified stiff-landings as having less than and soft landings as having more than 90 degrees knee flexion. Their research observed soft landings to have more work performed at the knee and hip.

The current research, however, demonstrated that this frequently used convention of soft- and stiff- landings is not appropriate to explain differences in work performed at the ankle and knee across landing tasks. The power clean had a small peak knee flexion angle, which would make it a stiff-landing, however work performed at the ankle was less than the block jump and drop landings. While the knee kinematics of the power clean correspond with the kinematic criteria for stiff-landing technique, the work performed at the ankle does not match the kinetic criteria, because only a small amount of work was performed at the ankle. In contrast, the drop landing met the kinematic criteria of soft-landing and the kinetic criteria for stiff-landing, as demonstrated by the large knee flexion angle and increased ankle work, respectively.

Rather than classify landing types as either soft or stiff, our data shows that the work performed at one joint is independent of work performed at another joint. Further, the kinematics of the segments forming the joint play a critical role in the work performed at that joint. For example, the postures of the foot and leg can be used to explain differences in ankle work performed across various landing types. The angle of the foot and leg rotation pre-impact influences the work performed by the plantar-flexors. The jump landing tasks had greater foot plantar-flexion and less leg forward rotation, thus a large amount of ankle work was performed to control rotations of these segments post-impact. The opposite was found for the weightlifting tasks, where a neutral foot position and greater forward leg rotation were observed at initial contact. Thus, in the weightlifting tasks, the postures of the foot and leg at initial contact were closer to their posture at peak knee flexion.

As differences in foot and leg postures were found between tasks at initial contact between jumping and weightlifting tasks, it can be put forth that the joint or segmental mechanics in the propulsion and flight phases of the specific tasks determine the landing postures. The similarities in foot and leg postures at initial contact in the drop landing and block jump tasks suggests the propulsion phase may be irrelevant in influencing posture at initial contact as no propulsion phase occurs in the drop landing. Rather, it can be theorized that the mechanics in the flight phase may be the most valuable predictor of kinematics at initial contact and subsequent kinetics during landing. To confirm this theory, the mechanics of the foot and leg during the flight phase and their impact on foot and leg kinematics at initial contact need to be studied.

The differences in joint and segment kinematics observed at peak knee flexion may also explain how work is performed across various landing techniques. The work performed at the knee is a result of knee extensor NJM eccentrically controlling thigh rotation as squat depth increases. At peak knee flexion, the greatest squat depths were attained in the clean and drop landing, whereas less knee flexion was observed for the block jump and power clean. The greater knee excursion was associated with more knee work performed in the drop landing and clean. However, across all tasks, knee work was found to dominate lower extremity work performed.

This finding highlights the contribution of the knee extensors to energy absorption during landing. Bobbert et al. (4) and DeVita et al. (13) have also found increased knee extensor work to be associated with greater squat depth during landing tasks. Palmeri-Smith et al. (28) found that quadriceps inhibition induced by knee joint effusion results in an extended knee position during landing. They found higher impact forces when landing with a reduced knee extensor moment. Due to the kinematics of the knee and a lack of available force from the knee extensors, they speculated that passive structures likely absorbed the energy at impact. A lack of knee extensor strength may limit the ability to land with greater knee flexion as knee extensor relative muscular effort increases with squat depth (7). Therefore, as less work is performed at the knee, work must be redistributed to other joints or absorbed via passive structures such as bone or ligament.

Knee extensor weakness is associated with anterior cruciate ligament injured individuals (28, 35). Recent research found anterior cruciate ligament deficient individuals land with less knee flexion and lower knee extensor NJM. To compensate, increased forward trunk lean and hip extensor NJM are present. This compensatory strategy has also been reported in squat exercise in anterior cruciate ligament injured individuals, where greater hip extensor and decreased knee extensor NJMs are observed (35). Landing from a jump or performing a squat exercise with increased forward trunk lean is far from ideal, due to the increased risk of falling in addition to reduced work performed at the knee (27). Other multi-joint tasks, such as lifting objects from the ground also require strong knee extensors. When lifting from the ground, individuals with weak knee extensors employ a back dominant strategy, increasing the stress on the soft tissue structures of the back and potentially the risk of falling forward (30).

A knee extensor strategy has been reported across a variety of multi-joint tasks where lowering the body into a squat position is required (7, 11, 15). Flanagan et al. (15) compared lower extremity joint contributions across three variations of the step exercises. They found the greatest demand on the knee extensors during the step-down task, which was attributed to the larger knee excursions in the step-down task. Similarly, Bryanton et al. (7) observed knee extensor relative muscular effort to increase with squat depth, suggesting the knee extensors were most activated in a deep squat (105°-119° knee flexion). Together, these studies describe an important role of the knee extensor musculature in multi-joint tasks – specifically to control the depth of squat allowing the total body centre of mass to be raised or lowered.

As the knee extensors are increasingly activated as knee flexion increases (7), the strength of the knee extensors is paramount to perform squat-type tasks. As previously discussed, knee extensor weakness associated with anterior cruciate ligament injury impairs squatting ability, further supporting the importance of knee extensor strength. The data from the present research provides insight into how the knee extensors may optimally be trained to improve muscular strength.

To impose stress on the knee extensors, exercises that require greater contribution from the knee extensors must be utilized (16). Although the drop landing had a high percentage (58%) of work performed at the knee, the highest knee extensor NJMs, in addition to a large knee excursion (clean only) were found in the weightlifting tasks. This research supports the use of weightlifting exercises, such as the clean and power clean to strengthen the knee extensors most effectively, as these tasks require the greatest contribution from the knee extensors to perform work. Due to the added constraint of the loaded barbell in weightlifting, to catch the bar on the shoulders and keep it supported across the shoulders, an erect trunk posture is critical. Kulas et al. (25) found that added trunk load and an erect trunk posture leads to more work performed at the knee. Further, Bryanton et al. (7) and Hartmann et al. (20) found increased squat depth leads loads the knee extensors to a greater extent than a partial squat. In this study, the greatest knee excursion and NJMs were found in the clean exercise. Therefore, our results, with support from others, suggest that to provide sufficient stimulus to stress the knee extensors, weightlifting tasks are most effective, particularly the clean.

To maximally load the knee extensors, proper movement mechanics are important. When a multi-joint movement, such as the squat is performed improperly, due to muscular weakness or lack of technique, it is likely that the non-targeted musculature will be strengthened. For example, in the squat exercise, to impose stress on the knee extensors, forward rotation of the leg is necessary (12, 17). Therefore, proper squatting mechanics include forward rotation of the leg. When the squat is performed improperly, such as when the leg does not rotate forward and the trunk leans forward, greater loading of the hip extensors and a subsequent decreased loading of the knee extensors occurs (17). These mechanics are similar to the compensatory strategy observed in anterior cruciate ligament injured individuals performing squat exercise (35). Thus, to ensure that the desired musculature is strengthened (i.e. knee extensors) when using exercises involving squatting, proper movement mechanics are required. In addition to barbell squat exercise, the present research finds jump landing and weightlifting tasks require similar movement mechanics.

To conclude, this research demonstrated that the knee extensors are essential to landing as all the greatest contribution to lower extremity work is work performed at the knee, regardless of landing task. Previously, research has demonstrated the consequences of knee extensor weakness when performing multi-joint movements (35). Thus, it is imperative that, in practice, exercises are performed properly, to strengthen the desired muscle groups and learn a movement pattern that can be used across a range of multi-joint tasks. These tasks include barbell squats, weightlifting exercise and jump landing. While different landing tasks exist, it appears that they share at least one generalized characteristic, which is that knee extensor work must be performed to control the depth of squat during landing. The importance of the knee extensors in landing tasks should be recognized in sport, particularly in strength and conditioning training so that these muscles are appropriately strengthened.

REFERENCES

1. Bobbert, MF, Huijing, PA, and Van Ingen Schenau, GJ. Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Med Sci Sports Exerc* 19: 339-346, 1987.

2. Bryanton, MA, Kennedy, MD, Carey, JP, and Chiu, LZF. Effect of Squat Depth and Barbell Load on Relative Muscular Effort in Squatting. *J Strength Cond Res* In Press.

3. Chiu, LZF, and Salem, GJ. Comparison of joint kinetics during free weight and flywheel resistance exercise. *J Strength Cond Res* 20: 555-562, 2006.

4. Chizewski, MG, and Chiu, LZF. Contribution of calcaneal and leg segment rotations to ankle joint dorsiflexion in a weight-bearing task. *Gait Posture* 36: 85-89, 2012.

5. DeVita, P, and Skelly, WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc* 24: 108-115, 1992.

6. Flanagan, SP, Kessans, KM, and Salem, GJ. Quantifying bilateral joint contributions during three variations of the step exercise. *J Sports Rehabil* 15: 255-265, 2006.

7. Flanagan, SP, and Salem, GJ. The Validity of Summing Lower Extremity Individual Joint Kinetic Measures. *J Appl Biomech* 21: 181-188, 2005.

8. Fry, AC, Smith, JC, and Schilling, BK. Effect of Knee Position on Hip and Knee Torques during the Barbell Squat. *J Strength Cond Res* 17: 629-633, 2003.

9. Hartmann, H, Wirth, KPDD, Klusemann, MMA, Dalic, J, Matuschek, C, and Schmidtbleicher, DPDhc. Influence of squatting depth on jumping performance. *J Strength Cond Res* In Press.

10. Kulas, A, Zalewski, P, Hortobagyi, T, and DeVita, P. Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings. *J Biomech* 41:180-185, 2008.

11. Oberländer, KD, Brüggemann, G-, Höher, J, and Karamanidis, K. Reduced knee joint moment in ACL deficient patients at a cost of dynamic stability during landing. *J Biomech* 45: 1387-1392, 2012.

12. Palmieri-Smith, RM, Kreinbrink, J, Ashton-Miller, JA, and Wojtys, EM. Quadriceps inhibition induced by an experimental knee joint effusion affects knee joint mechanics during a single-legged drop landing. *Am J Sports Med* 35: 1269-1275, 2007.

13. Puniello, MS, McGibbon, CA, and Krebs, DE. Lifting strategy and stability in strength-impaired elders. *Spine* 26: 731-737, 2001.

14. Salem, GJ, Salinas, R, and Harding, FV. Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil* 84: 1211-1216, 2003.

15. Zhang, S, Bates, BT, and Dufek, JS. Contributions of lower extremity joints to energy dissipation during landing. *Med Sci Sports Exerc* 32: 812-819, 2000.