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*Published in:*
Journal of Fitness Research

FitnessResearch.edu.au

INDUSTRY EDUCATION

# PRACTICAL APPLICATIONS OF BIOMECHANICAL PRINCIPLES IN RESISTANCE TRAINING: MOMENTS AND MOMENT ARMS

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## ABSTRACT

Exercise professionals routinely prescribe resistance training to clients with varied goals. Therefore, they need to be able to modify the difficulty of a variety of exercises and to understand how such modifications can alter the relative joint loading on their clients so to maximise the potential for positive adaptation and to minimise injury risk. This paper is the first in a three part series that will examine how a variety of biomechanical principles and concepts have direct relevance to the prescription of resistance training for the general and athletic populations as well as for musculoskeletal injury rehabilitation. In this paper, we start by defining the terms moment (torque), moment arms, compressive, tensile and shear forces as well as joint stress (pressure). We then demonstrate how an understanding of moments and moment arms is integral to the exercise professionals' ability to develop a systematic progression of variations of common exercises. In particular, we examine how a variety of factors including joint range of motion, body orientation, type of external loading, the lifter's anthropometric proportions and the position of the external load will influence the difficulty of each exercise variation. We then highlight the primary results of several selected studies which have compared the resistance moment arms and joint moments, forces or stresses that are encountered during selected variations of common lower body resistance training exercises. We hope that exercise professionals will benefit from this knowledge of applied resistance training biomechanics and be better able to systematically progress exercise difficulty and to modify joint loading as a result. The two remaining articles in this series will focus on the neuromechanical properties of the human musculoskeletal system and better understanding the biomechanical implications of a variety of alternative resistance training techniques, respectively.

**Keywords:** biomechanics; forces; joint loading; moments; resistance training progressions.


ISSN 2201-5655 

## INTRODUCTION

In this three part series, we will explain the relevance of several key biomechanical principles and concepts to the prescription of resistance training for athletic, general population and rehabilitation clients. This, the first paper in the series, will focus on how the concepts of moments (also commonly referred to as torques) are integral to the understanding of resistance training progression and in reducing or increasing the loads across particular joints and muscles. In particular, we will describe how these moments and joint loads may change as a function of: 1) Joint range of motion; 2) Body orientation; 3) Type of external loading; 4) Lifter's anthropometric proportions; and 5) Position of the external load. However, in order to achieve these objectives, we will first need to define: 1) Tensile, compression and shear forces and stress (pressure); and 2) Moments and moment arms. Following this, a brief review of some relevant studies that have examined how the joint loads change as a function of the manner in which exercise is performed is provided. The selected studies all examined common multi-joint lower body exercises and appeared to use well-validated biomechanical models in their analyses.

Biomechanical Definitions: Forces and Stress

A number of internal forces are produced during resistance training and activities of daily living. Muscular forces are internal forces that are transmitted via tendons to bones that tend to cause movement of the distal segment. During these activities, passive forces are also developed in the ligaments spanning the relevant joints so to minimise unwanted movements and to provide greater joint stability Resistance training is typically prescribed to increase one or a combination of strength, power, endurance or hypertrophy of the musculoskeletal system (muscles, bone, tendons and ligaments), with the ultimate aim of improving physical performance, appearance and health while reducing the risk of musculoskeletal injury in sport or activities of daily living. In essence, the greater the forces applied to the body during resistance training, the greater the potential for improved physical performance and joint stability due to the positive adaptations in the muscles, bones, tendons and ligaments. However, if these forces are too large and encountered too often, injury may also occur. For a review of the injuries associated with the resistance training sports of bodybuilding, powerlifting and Olympic weightlifting please consult a book chapter [1] as well as a more recent study on strongman training [2]. Therefore, the exercise professional needs to understand how the resistance exercises they prescribe and the way each client performs these exercises will dictate the outcome.

Resistance forces resulting from external loads (e.g. bodyweight or resistance training equipment such as dumbbells, barbells and cables) requires the production of muscular forces to counteract their effects. In addition to muscular forces, resistance training both generates and relies on, other internal forces including compressive, tensile and shear forces as well as stress (pressure). These factors also need to be considered in terms of exercise safety. A description of these concepts and some anatomical examples are given in Table 1.

## BIOMECHANICAL DEFINITIONS: MOMENTS AND MOMENT ARMS

When a load e.g. a dumbbell acts at a distance from an axis of rotation (e.g. joint centre), rotation of the affected segment tends to occur. The moving body segments can be described as levers, with examples of all three lever order systems present in the human body. Nevertheless, the most common lever in the human body is the third class system in which the resistance force(s) have a larger moment arm than the muscle force(s). While this arrangement reduces the strength across the joint, it allows large ranges and speed of motion. This tendency to rotate is called a moment (or torque) and is most easily calculated as the product of the magnitude of the force (F) and the length of the moment arm (MArm) (see Equation 1). While we may typically focus on the extension and flexion moments for many resistance exercises like the back squat, deadlift, chin ups, and bicep curls, moments can be applied in all three planes of motion.

**Equation 1**

M = F x MArm (Eq. 1)

where M = moment; F = magnitude of the force and MArm = length of the moment arm.

The moment arm of the resistance force is defined as the perpendicular distance between two parallel lines, these being through the joint centre and the point of force application, with both lines oriented in the direction of the force. When performing any free weight or bodyweight exercise, the line of the resistance force is vertically downward due to gravity. Hence, in order for the resistance moment arm to be perpendicular to the line of the vertical force in these exercises, the resistance moment arm must be the horizontal distance from the line of the force and the parallel line through the joint centre. See Figure 1 for an example of how the resistance moment arms and therefore the difficulty of the exercise change throughout the range of motion for the bicep curl.

We typically try to progressively increase the load lifted during resistance training. Any increase in load increases the resistance force, which will in turn increase the joint moment and require more muscular force to perform the exercise (see Equation 2 for an isometric action).

**Equation 2**

MJ = MR (Eq. 2)

FM x MArmM = FR x MArmR

where MJ = joint moment; MR = resistance moment; FM = magnitude of the muscle force; MArmM = length of the muscle moment arm; FR = magnitude of the resistance force; MArmR = length of the resistance moment arm.

The complexity of the human body creates some potential challenges to the application of Equation 2. The first issue is that most resistance exercises involve multiple resistance and muscular forces. As an example in the dumbbell bicep curl, the forearm, hand and dumbbell provide the resistance forces and this is opposed by the combined action of several agonist muscles including the bicep brachii, brachialis

Table 1: Definitions, examples and implications of tensile, compressive and shear forces and stress within the body.

| Type of Force | Definition | Examples and Implications |
|---|---|---|
| **Tensile force** | A force that tends to pull two tissues apart. | Hanging from a chin up bar whereby the weight (downward force caused by gravity) of the body tends to decompress (separate) the vertebrae. Forces that tend to pull apart (rupture) the posterior and anterior cruciate ligaments during common leg exercises such as leg extensions, leg curls and lunges. |
| **Compressive force** | A force that tends to push two tissues together. | Performing a squat whereby the barbell load and the upper body's weight tends to compress the lumbar vertebrae. Performing a forward lunge whereby the weight of the barbell load and the lifters body weight as well as their forward momentum tends to compress the femur and tibia and internal knee joint structures. |
| **Shear force** | A force that tends to cause two tissues to slide past each other. | Performing a bent over row whereby the barbell load and upper body tends to cause the back to round and the lumbar vertebrae to slide past each other, stressing structures such as the lumbar ligaments and vertebral discs. Performing a knee extension whereby the femur and tibia tend to slide past each other and increasing the load on the anterior cruciate ligaments. |
| **Stress** | The magnitude of an internal force over a given anatomical area. This is calculated in the same way as the pressure in a fluid. | The compressive force of bodyweight and any other external load acting on an anatomical structure of a given area e.g. the lumbar vertebrae during the squat. Changes in the loading (stress) acting on the patellofemoral (knee) joint throughout the range of motion of a squat. |

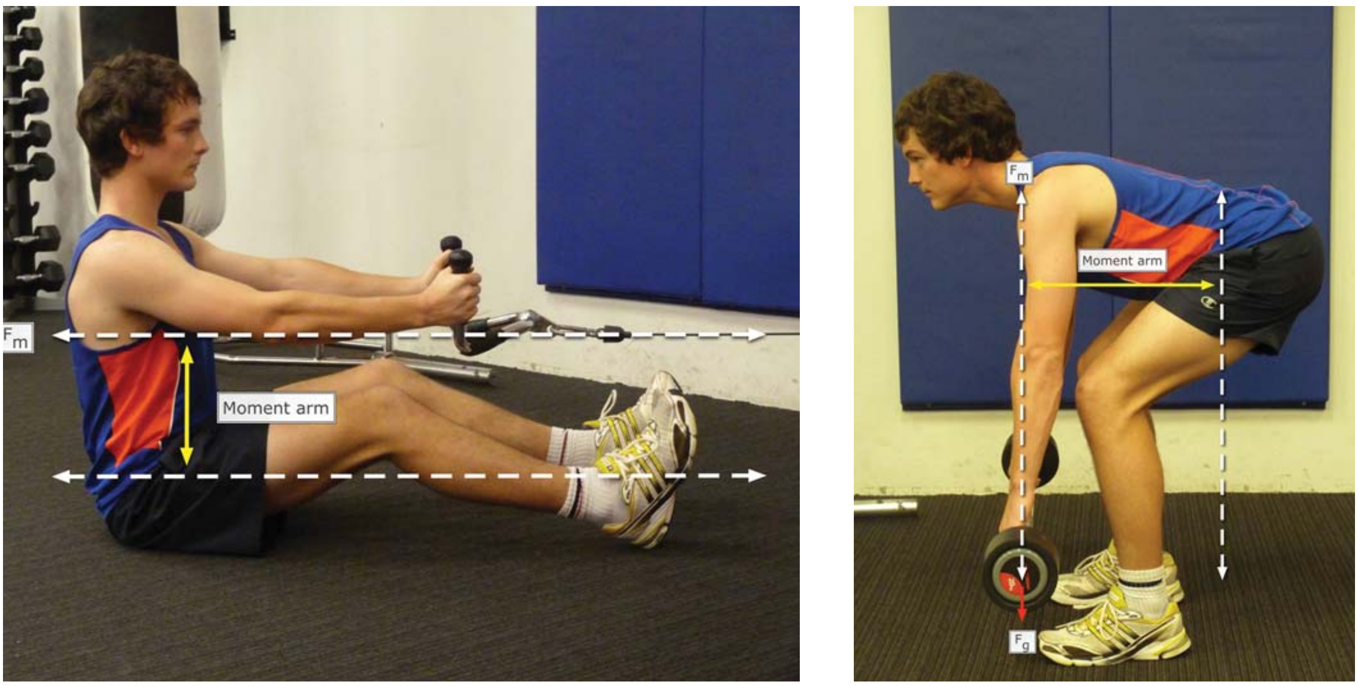
1a 1b 1c

Figure 1: Changes in the resistance moment arms at three points of the range of motion of the bicep curl.

and brachioradialis. It is also acknowledged that each muscle's moment arm changes throughout the range of motion. As many muscles with different attachment points and moment arms contribute to the overall muscle force during single-joint and multi-joint exercises, it is almost impossible to easily understand how all of these may change throughout the range of motion of an exercise. For the sake of simplicity, we will therefore ignore the potential changes in muscle moment arms, assume that all agonist muscle forces act at one point and focus on the position of the relevant resistance forces and hence resistance moment arm lengths throughout this paper.

The concept of resistance and joint moments can also be applied to multi-joint exercises like the squat, deadlift, bench press and cable row. The joint resistance moment arms for the lumbar spine are shown in Figure 2 for a seated cable row and bent over row. For exercises like the cable row, the line of the resistance force, which is indicated by the cable, is horizontal, which differs to the bent over row in which the resistance force acts vertically. As a moment arm is the perpendicular distance from the line of the force to the joint centre, the resistance moment arm must be vertical for the seated cable row and horizontal for the bent over row.

Figure 2: Differences in the direction of the lumbar spine resistance moment arms in the seated cable row (Figure 2a) and bent over row (Figure 2b).



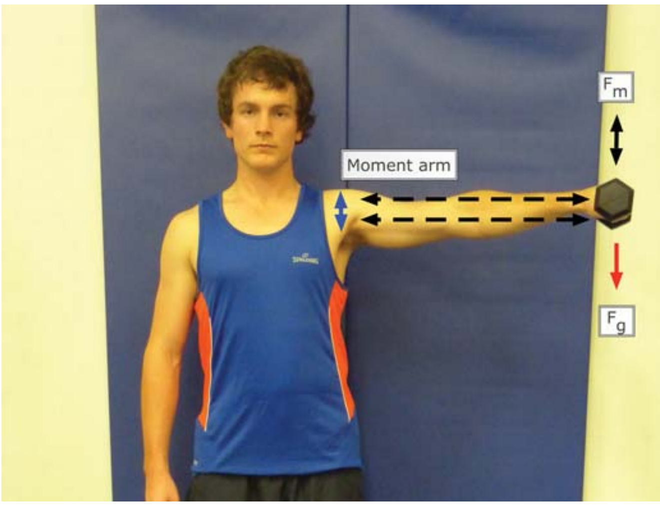

2a 2b

## VARIATIONS IN RESISTANCE AND JOINT MOMENTS AS A FUNCTION OF BODY ORIENTATION OR TYPE OF EXTERNAL LOADING

Many resistance-training exercises have variations in which the relative orientation of different body parts change with respect to gravity. For example, while a dumbbell lateral raise is normally performed standing upright, it can also be performed unilaterally while lying on one's side on an incline or flat bench. Figure 3 demonstrates how three versions of the dumbbell lateral raise differ with respect to what range of motion the resistance moment arm is maximised.

As a dumbbell provides the resistance force (Figure 3), we know that the resistance moment arm is maximised when the arm is horizontal, and, as a consequence, so too is the muscle force and joint moment. This means that when the dumbbell lateral is performed standing upright, the resistance moment arm, muscle force, and joint moment is maximised at 90º of shoulder abduction (Figure 3a). In contrast, when the exercise is performed with the exerciser lying down on a flat bench (Figure 3b), the resistance moment arm, muscle force, and joint moment is maximised with the arm adducted (0º abduction – arm touching the side of the body), and when lying on an incline bench set at ~45º these are maximised at 45º of abduction (Figure 3c). This principle can be applied to many other exercises including bicep curls, tricep extensions and external shoulder rotations, meaning that the exercise professional can manipulate the range of motion in which the greatest muscular and joint loads are applied. Another way to manipulate the range of motion in which the greatest loads are applied to the muscles is via using cable resistance (see Figure 4).

As seen in Figure 4, the resistance moment arm of the cable lateral raise is maximised when the shoulder joint is close to full abduction (i.e. arm close to vertically downward) at the start of the concentric phase as the line of force, as indicated by the cable, is almost horizontal. This means that the cable version loads the deltoid to a much greater extent in




3a


3b


3c

Figure 3: Differences in the relative shoulder joint range of motion where maximal resistance is felt in a standing (Figure 3a), lying (Figure 3b) and inclined (Figure 3c) position while performing the dumbbell lateral raise.

an adducted (lengthened) position whereas the dumbbell loads the muscle in the abducted (shortened) position. When performing the cable version, the resistance moment arm is reduced throughout the concentric range of motion as the perpendicular distance from the line of the resistance force (cable) to the shoulder joint decreases. However, the variation in the length of the resistance moment arm and hence resistance moment is much less in the cable than dumbbell version. This means that there is likely to be a more constant activation of the deltoid muscle in the cable version, with bodybuilders typically referring to this as more constant muscular tension throughout the range of motion.

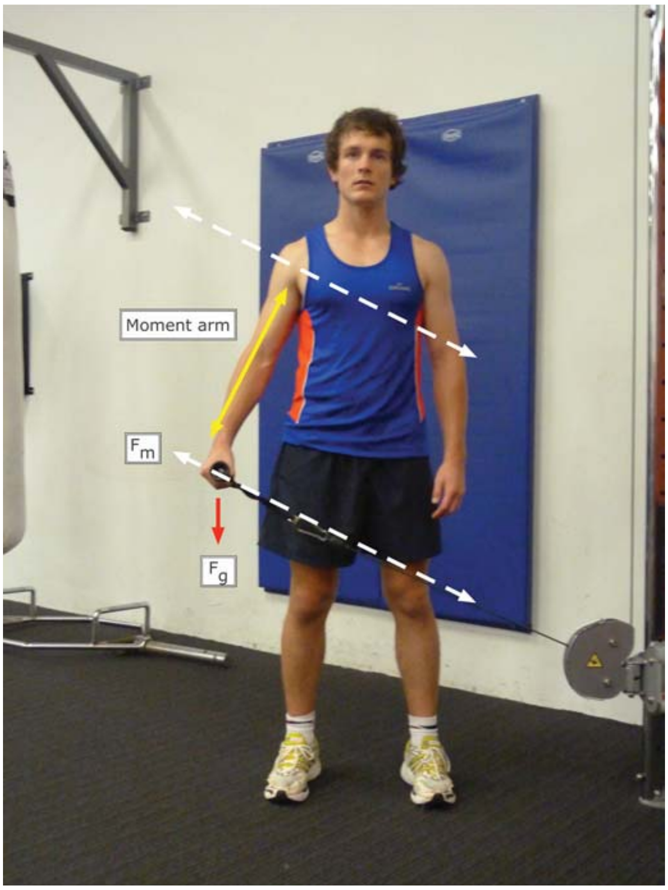



Figure 4: Position where the maximum resistance moment arm occurs for the cable deltoid lateral raise.

## VARIATIONS IN JOINT LOADING AS A FUNCTION OF LIFTER ANTHROPOMETRY

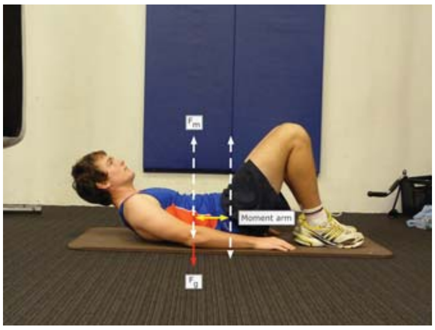
When resistance exercise forms the basis of a sport, athletes who are taller or have longer limbs are often at a mechanical disadvantage. This has been supported by studies involving Powerlifters [3; 4] and Olympic Weightlifters [5], and is important because rather than manipulate resistance moment arms to make a sporting event like the competition bench press harder, athletes aim to achieve maximum mechanical efficiency so to lift the greatest loads during these sports. Taller lifters, with longer segments, are automatically presented with increased resistance moment arms during most competitive exercises, compared to their shorter limbed counterparts. For example, in events such as the bench press and squat, lifters with long forearms and thighs, respectively will need to lift the load a greater distance than their shorter limbed peers. These longer limb segments will therefore increase the resistance torques and work (force multiplied by displacement) required to lift these loads. This means that to complete the same competitive lift with the same load they must increase the muscle force that they can apply while maximising technical efficiency to ensure that the line of the resistance force stays as close to the primary joints as possible.

In contrast, in some exercises longer limbs are an advantage. For example, in the deadlift long arms may be useful as they would allow the lifter to position their trunk more vertically at the start of the lift which would reduce the lumbar resistance moment arms and work required to perform the lift.

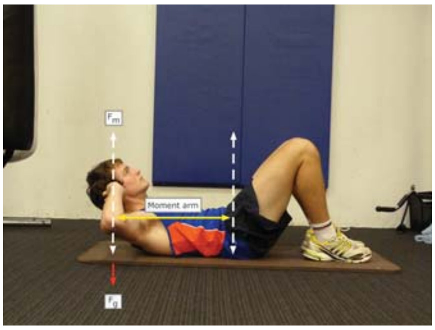
## VARIATIONS IN JOINT LOADING AS A FUNCTION OF LOAD POSITION

The position of the load and hence the length of resistance moment arm can be easily modified in many exercises to make them easier or harder. This can be seen in many single joint such as crunches, back extensions and deltoid raises whereby the further the resistances are positioned away from the joint centres, the harder the exercise becomes. For crunches and back extensions, this means that the position of the arms and/or external loads can have

Figure 5: Differences in the resistance moment arms of the upper limb as a function of the position of the upper limbs with respect to the lumbar spine in a crunch. Figure 5a (hands near hips), Figure 5b (hands around ears) and Figure 5c (hands outstretched above the head) show increasing resistance moment arms and hence an increase in exercise difficulty. Note: These differences in resistance moment arms are not completely accurate as they do not take into account the resistance moment arm of the trunk and head. Hence, the real difference in exercise difficulty will not be quite as large as demonstrated in the figures. However such a principle applies to doing weighted crunches, whereby the position of the weight is often more important than the amount of weight




5a

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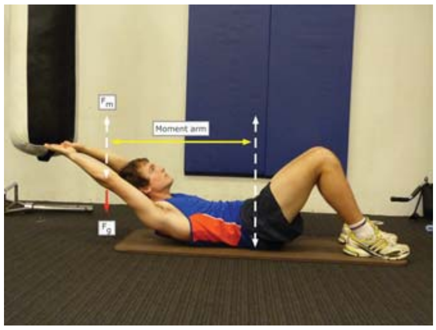


5c

a greater influence on performance than the actual magnitude of any external loads (see Figure 5). Similar concepts can be applied to multi-joint bodyweight exercises like push ups and inverted rows, whereby the length of the resistance moment arm can be reduced by performing knee or wall push ups and bent knee inverted rows, respectively.

Changing the type of load (barbell, dumbbell, sandbag, etc), relative position of the external load and/or the path in which the load travels during exercises like the squat, deadlift, bent over row, bench press and shoulder press can also change the resistance moment arm, and as a consequence, the muscle forces that must be applied and subsequent joint moments. Excellent examples of this can be seen in the squat and deadlift, with front squats, low bar back squats and high bar back squats as well as conventional and hex/trap bar deadlifts some of the relevant options. These two deadlift variations are illustrated, with their respective resistance moment arms in Figure 6.

On this basis, an increasing research focus in resistance training biomechanics has been to quantify how variations in the position of the load and/or body segment(s) position alter the resistances moment arms and joint moments as well as the


6a


6b

Figure 6: Differences in the resistance moment arms around the lumbar spine as a function of the position of the barbell in the conventional (Figure 6a) and hexagonal (hex) bar (Figure 6b) deadlift versions.

Table 2. Selected studies examining variations in joint loading and moment arm lengths at key points of the ascent phase of different variations of common multi-joint lower body exercises.

| Exercise | Versions Compared | Study | Primary findings |
|---|---|---|---|
| Squat | Trad, PL and Box | Swinton et al. [11] | Exercise variation influenced both moment arm length and joint moments. Moment arm length tended to decrease from Trad to PL to Box squats, but was not influenced by load. Lower back moments were maximised during Trad squats, hip moments, both extension and abduction, during PL squats, knee moments during Box squats, and ankle moments during Trad squats. |
| Squat | Narrow, medium and wide stance | Escamilla et al. [6] | Ankle moment arm length and joint moments typically maximised during Wide stance squats, decreasing from Wide to Medium to Narrow. Similar patterns observed for both hip and knee joints too, but differences were less consistent. For example, differences in hip and knee joint moments only occurred when the knee joint was flexed 45°. A similar pattern was noted for moment arm length. |
| Deadlift | CDL and SDL | Escamilla et al. [7] | Moment arms and joint moments at the hip were not influenced by exercise variation. In contrast, barbell mass and combined system mass were located more posterior to the knee during the SDL, resulting in significantly greater extension moments at the knee (peak moment approx 3-fold greater) in comparison to the CDL. |
| Deadlift | CDL and HBDL | Swinton et al. [10] | The use of a hexagonal barbell resulted in shorter moment arms at lower back, hip and ankle. At the knee the load position was reversed to create a resistive flexor moment. These changes resulted in significantly lower extension moments at lower back and hip, with significantly greater extension moments at the knee during the HBDL compared to the CDL. |
| Forward Lunge | SSFL and LSFL; Stationary vs striding | Escamilla et al. [8] | PTF compressive force and stress was greater with increased knee flexion. Between 70-90° of knee flexion, PTF force and stress was greater for a STFL than LSFL. Between 10-40° of knee flexion, PTF force and stress was greater for a stepping forward lunge than a stationary lunge (split squat) with no step forward. |
| Forward Lunge | SSFL and LSFL | Escamilla et al. [9] | All lunge variations examined produced very low mean ACL TF, suggesting all are applicable for ACL rehabilitation clients. Alternatively, all lunge variations produced quite high PCL loading, meaning that these exercises should be cautious in using them with PCL rehabilitation clients. Mean PCL TF was greater in LSFL than SSFL between 0-80° of knee flexion; as well as in stationary than stepping forward lunge between 0-20° of knee flexion. |

* Trad = traditional squat; PL = powerlifting squat; Box = box squat Narrow; CDL = conventional deadlift; SDL = sumo deadlift; HBDL = hexagonal bar deadlift; SSFL = short step forward lunge; LSFL = long step forward lunge; PTF = Patello-femoral compressive force; ACL = anterior cruciate ligament; TF = tensile force; PCL = posterior cruciate ligament.

associated joint compressive, tensile and shear forces and stresses. Table 2 lists examples of selected studies that have compared variations of common multi-joint lower body resistance exercises [6; 7; 8; 9; 10; 11]. Interested readers should also consult other studies that have examined joint loads in resistance training exercises and how these can be modified by alterations in exercise technique [12; 13; 14; 15; 16; 17; 18].

While only a snapshot of the relevant literature, a number of practical applications can be drawn from the results presented in Table 2. The first is that the relative joint loading on the lower back and hip extensors (e.g. erector spinae, gluteus maximus and hamstrings) can be increased by having the resistance moment arm further in front of the hip and lower back and by adopting a more horizontal trunk position at the bottom position of exercises like the squat and deadlift. In contrast, greater knee joint and quadriceps loading can be achieved by having the load closer to the hip and lower back and by maintaining a more upright trunk position. When performing lunges, stepping forward with each step will increase the front leg's compressive knee joint force and stress but reduce the posterior cruciate ligament tensile force in early knee flexion compared to stationary lunges (split squats) that involve no step. Lunges with a shorter step may increase the front leg's compressive knee joint force and stress but reduce the posterior cruciate ligament tensile force compared to a longer step. Such information may be vital when designing resistance training program progressions for clients at risk or recovering from a variety of knee injuries.

## CONCLUSIONS

We hope that this article has explained how an understanding of moment arms and joint moments is fundamental to best practice in resistance exercise prescription. These concepts will allow the astute exercise professional to better match their exercise prescription to each client's unique requirements and goals. Exercise professionals can achieve this by keeping up to date with new research findings and by applying their knowledge of functional anatomy and visual observation skills to predict how variations in exercise performance will likely alter the relative load at different joints and anatomical structures. The next article in this series will focus on explaining how a number of neuromechanical properties of the human musculoskeletal system may also be relevant to providing a more effective and safe exercise prescription.

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