Forms of Variable Resistance Training

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SUMMARY

RESISTANCE TRAINING METHODS HAVE BEEN BROADLY CLASSIFIED INTO 3 CATEGORIES: CONSTANT, ACCOMMODATING, AND VARIABLE RESISTANCE. VARIABLE RESISTANCE TRAINING METHODS, WHICH INCLUDES CAMS AND LEVERS, CHAINS, AND RUBBER-BASED RESISTANCE, WILL BE THE FOCUS OF THIS ARTICLE. THE KINEMATICS, KINETICS, AND HUMAN STRENGTH CURVE CHARACTERISTICS ASSOCIATED WITH THESE 3 TYPES OF VARIABLE RESISTANCE ARE DISCUSSED, GIVEN THAT EACH RESISTANCE TYPE MAY OFFER A UNIQUE SET OF MECHANICAL STIMULI AND, HENCE, MUSCULOSKELETAL ADAPTATIONS. THE PRACTICAL APPLICATIONS AND LIMITATIONS ASSOCIATED WITH EACH FORM OF VARIABLE RESISTANCE WILL ALSO BE CONSIDERED.

INTRODUCTION

Resistance training, once used by a very small group of elite athletes and weight lifting enthusiasts, has grown immensely in popularity during the past 3 decades and is currently practiced by a large number of people within society. There are many modes of resistance training and a multitude of variables that can be manipulated to benefit the musculoskeletal system. In terms of the modes of resistance that can be used to induce musculoskeletal adaptation, 3 broad categories typically are used: constant external resistance, accommodating resistance, and variable resistance (VR). Constant external resistance is defined as an unchanging external load throughout the range of motion and is the most popular form of resistance training, because many believe it better simulates real-life activities and provides a more natural coordination of the musculature (32,48,56). Accommodating resistance equipment is designed to exert speed controlled or isokinetic resistance throughout the full range of motion, more recently termed semi-isokinetic resistance (60). Fluid-based resistance remains undefined, because it resembles both accommodating and VR. Hydraulic (liquid-controlled) and pneumatic (gas-controlled) equipment are 2 forms of fluid resistance. VR equipment is designed to change the external resistive load throughout an exercise’s range of motion; the different types of VR equipment include rubber-based resistance (RBR), chains, and cam and lever systems.

To assist in understanding some of the concepts discussed in this article, a basic knowledge of human strength curves, kinematics, and kinetics and their importance in explaining the adaptive potential of an exercise, loading scheme, and resistance type are required because it is the mechanical stimuli that dictate the hormonal and metabolic responses. Kinematics describes the change in position of an object via variables such as position, displacement, time, velocity, and acceleration (28). Kinetics describes the forces and their effects on the motion or kinematics of an object (51). Each type of resistance can offer a unique set of kinematics and kinetics and therefore differential musculoskeletal adaptation.

Human strength curves are based on movements about single joints using 2-dimensional coordinate systems but also have been extended to include multi-joint movements with the use of 3-dimensional coordinate systems. Strength curves are classified into 3 categories: ascending, descending, and bell-shaped, which are determined by the force-angle (torque) relationship within the musculoskeletal system (Figure 1) (24,40,66,67). Multi-joint strength curves are calculated by summing the torques of all involved joints in the exercise movement, which provides an overall measure (estimate) of the maximum muscular capability in the system; for example, during the traditional squat, a sum of torques would be determined by adding the individual torques produced at ankle, knee, hip, and trunk, respectively. The percentage of force and torque produced at each joint may vary depending on the mode of resistance, exercise movement, velocity of movement, and the amount of external resistance lifted; however, further investigation is required to determine the exact contribution of the involved musculature and joints (23). Strength curves have been developed by theoretical and experimental means. Theoretical strength curves predict the torque capabilities of the musculoskeletal system through cadaver dissection where the following physiological and biomechanical

KEY WORDS:
biomechanics; rubber bands; steel chains; cams and levers; kinematics; kinetics
Three major strength curves: force production versus joint angle.

Strength curves approximate the torque (relationship between force generation and joint angle) production capabilities for specified exercise movements (37). Strength can be defined as the maximal force and torque (rotational force) a musculoskeletal lever system can generate at a given velocity (18,38). Muscular force generation and torque production are dependent upon a number of physiological, biomechanical, and neural factors, including muscle cross-sectional area, muscle length, pennation angle, the radius of the internal and external moment arms, contraction speed, and the size, number, and type of motor units recruited (20,21,40).

Human strength curves of single joint movements (see Figure 1) are generally easy to categorize, as movement is generated via a single muscle or group of muscles (i.e., biceps brachii, brachialis, and brachioradialis muscles) with proximal insertion points causing rotation about a single axis (1 degree of rotational freedom), such as flexion-extension, adduction-abduction, elevation-depression, or internal rotation-external rotation. The dumbbell arm curl can be used to explain the relationship between internal forces acting within and external forces acting on the musculoskeletal system. During the dumbbell arm curl, the biceps brachii, brachialis, and brachioradialis muscles must produce a force and create a torque that is greater than that created by the weight of the dumbbell to cause a concentric contraction and flexion at the elbow. Biomechanically, the biceps brachii, brachialis and brachioradialis muscles generate an internal force that is transferred through their respective tendons, creating torque about the elbow leading to an external endpoint force that is applied to an external resistive load (e.g., dumbbell) leading to rotation about the elbow joint (66).

Multi-joint movements are complex and more difficult to categorize because movement occurs about multiple joints (multiple degrees of rotational freedom) in multiple planes and must be represented by 3-dimensional coordinate systems. Torque capabilities during multi-joint movements are influenced by a number of physiological and biomechanical factors, including the architecture of the involved musculature and joints, the type(s) of coordinated muscle actions, and the location of origin and insertion points. The majority of sport movements, such as running, kicking, and throwing, occur in sequential order, where movement is initiated by the larger proximal muscles and segments, and then transferred to smaller distal muscles and segments along the kinetic chain. This phenomenon is known as the summation of forces and or the summation of speed principle (10,28). During many multi-joint movements, the accumulation of forces generated about each joint along the kinetic chain results in an assimilation of joint torques; exercise movement examples include the bench press, leg press, squat, deadlift, and power clean (10). When the segments of these multi-joint movements approach full extension, the musculoskeletal lever system gains a mechanical advantage and is able to bare larger external resistive forces; theoretically these movements would be supplemented well by VR equipment that increases in a linear or curvilinear fashion (66).

Exercises with ascending strength curves include the squat, deadlift, bench press, leg press, and shoulder press. In these exercises, maximum

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strength and force production capability occur near the apex of the lift (24). In a descending strength curve, maximum strength is produced at the start of the lift, examples include bent-over and upright rows, pull-ups, chin-ups, and lat pull-downs. Single joint exercise movements generally have bell-shaped strength curves (e.g., elbow flexion and extension and knee flexion and extension), where maximum strength occurs around the mid-phase of the lift (24). The reader needs to be cognizant of the fact that human strength curves are generalized to the samples studied, as biomechanical and physiological differences between body segments and individuals are complex and not always accounted for.

Current forms of VR equipment include cams and levers, rubber-based resistance (RBR), and chains. These forms of resistance are used throughout the sport science, strength and conditioning, rehabilitation, powerlifting, and weightlifting world. In theory, if the equipment is designed to match the different human strength curves, then the contracting muscles would maximize force production throughout the range of motion and maximal gains in strength would be achieved (22). Whether this is actually the case and the practical relevance of VR training modes are not well understood, which provides the focus of subsequent discussion.

**Forms of Variable Resistance Training**

CAMs AND LEVERS

Lever and cam systems are designed to change the external moment arm (the length or radius) of the corresponding lever or cam to approximate the body’s changing moment arm (leverage and mechanical advantage) during the lift, which forces the muscles to exert near maximal effort throughout the range of motion (59). Therefore, the system attempts to provide resistance changes to match the musculoskeletal systems ability to produce torque at various joint angles along the movement path (26,32). Mechanical advantage is a product of the force–joint angle relationship, where the force exerted by the muscles will vary with the mechanical advantage of the joints associated with a specific movement (64). An “irregular-shaped cam” designed by Herz of Vienna in 1901, allowed for increased resistance at points where strength was greatest and decreased the resistance at points where the strength was lowest, accommodating for the musculoskeletal systems mechanical advantage, supposedly leading to improvements in strength (37). This design was adapted by Jones, the inventor of Nautilus, who in his equipment design used a shell-shaped cam very similar to that of Herz. Jones designed his first prototype in 1948 and then released the first cam run Nautilus machine onto the market in 1970 (58). Several years later, in 1972, Ariel designed the “dynamic variable resistance” machine, which used an external lever arm to match the musculoskeletal changing lever system for numerous exercise movements (2).

**Kinematics and Kinetics of Cams and Levers**

Lever and cam systems create a varying torque that opposes and corresponds to the torque production ability of the different musculoskeletal lever systems (38). In other words, the machines resistive torque attempts to match human torque capabilities for uniarticular movements, such as leg extensions, leg curls, bicep curls, and pullovers (37). The equation for torque is as follows:

\[ \text{Torque} = \text{Force (Newtons)} \times \text{Length of Movement Arm (Meters)} \]

From this equation, it can be observed that torque may be altered by either changing the amount of external or internal force acting on or within a body segment, or by changing the length of these respective moment arms. The moment arm is the perpendicular distance from the fulcrum (axis of rotation) to the point of force application (external load or tendon attachment). The length of the moment arm is proportional to the joint angle between 2 longitudinal segments during uniarticular movements, which is known as a relative joint angle (shown in Figure 2).

Cam and lever systems have a fixed resistive load; therefore, the external resistance is varied by altering the length of the moment arm or radius and hence the changing radius of an “irregular shaped cam” (Figure 3). A cam system’s resistive torque increases in proportion to the radius of the cam; therefore, the larger the radius, the greater the resistance and vice versa (30). The same can be said for lever systems, where length changes in the effective lever increase or decrease the effective resistance throughout the exercise movement. Three notable
cam shapes with varying moment arms have been designed by Nautilus, Universal, and other manufacturers, to match the machines resistive torque to human torque capabilities for specific exercises (Table 1).

The cams changing radius is designed to minimize the negative effects of momentum by matching external resistance to the internal force and torque generating capabilities (mechanical advantage) of the musculature, theoretically causing the working muscles to exert maximum force throughout the complete range of motion. Angular impulse is proportional to the amount of applied torque produced over time; therefore, angular impulse should be greater when cam-based machines are used, as the working muscles should be producing near maximal force/torque values over a longer period of time than constant external resistance modes. Given that mass remains constant, the net result of an increase in angular impulse should be an increase in average angular velocity, which is a desirable training goal for many athletic movements.

Hay and Andrews (34) studied the biomechanical effects of the Universal arm curl machine versus barbell arm curls and found that the machine provided a VR more consistent with the working muscles capacity to exert force throughout the range of motion than the barbell curl. They found that the barbell curl was inferior to the Universal arm curl machine, in terms of matching the external resistance and the muscular force capabilities of the elbow flexors at varying joint angles (see Figure 4) (59). Johnson et al. (37) compared human torque capabilities and machine resistive torque by using 4 Eagle cam-based resistance machines that included knee extension, knee flexion, elbow extension, and elbow flexion. They found that the 4 machines accommodated the subjects fairly well by creating machine resistive torque curves similar to human torque curves, an example of which can be observed in Figure 5. It must be noted that as a result of individual variations of size and strength, it is difficult to construct a machine that accommodates everyone’s unique anthropometry. Regardless of this inherent limitation, cam and lever systems have grown in popularity and are currently used in many fitness and rehabilitation centers worldwide. The benefits and

| **Table 1** Human strength curves for various cam based exercise movements (adapted from Fleck and Kraemer [24]) |
|---|---|---|---|
| **Strength curve** | **Ascending** | **Descending** | **Bell-shaped** |
| Exercise example | Deadlift | Seated row | Elbow flexion and extension |
| Chest press | Lat pull-downs | Knee flexion and extension |
| Squats | Ability of muscle to produce force and create torque is lowest at the start of lift and increases throughout the ascent phase due to an increase in mechanical advantage. | Ability of muscle to produce force and create torque is greatest in the first quarter of the lift and progressively decreases throughout the last three quarters of the lift as the mechanical advantage diminishes throughout the lift. | Ability of muscle to produce force and create torque is highest during the middle portions of the lift and lowest in the first and last quarter of the lift. |

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limitations of their use are now discussed.

Practical Applications of Cams and Levers. As mentioned previously, the most notable benefit to using cams is their ability to create a resistance system that matches the musculature’s ability to generate force and produce torque throughout the entire range of an exercise. Cam and lever equipment is suitable for beginner and weak resistance trainers because it follows a fixed movement path and requires less skill, decreased intermuscular co-ordination, and is less likely to cause injury compared with other modes of resistance because it is easier to maintain control of the load (26,29,32,33). It allows for unilateral and bilateral training options and no spotter is required. Furthermore, the use of such cams is common in the rehabilitation setting where single joint (i.e., rotation about a single joint axis) and multi-joint (i.e., rotation about 2 or more joint axes) exercise movements are used in combination for the rehabilitation of injuries (e.g., anterior cruciate ligament reconstructions) and certain pathologies, such as patellofemoral pain syndrome (25,45).

Single joint movements (e.g., knee extension and flexion) have the capability to isolate specific muscle groups (e.g., the quadriceps and hamstrings), which can be beneficial when correcting muscle imbalances. Patellofemoral pain syndrome (patellar malalignment) is thought to be caused by a strength imbalance between the vastus lateralis and vastus medialis, which can be remedied by using single-joint movements in combination with multi-joint movements to increase vastus medialis strength (16). In general, multi-joint movements (i.e., traditional squats) produce greater compressive forces and single joint movements (i.e., leg extensions) produce greater shearing forces on the involved joints (e.g., knee) and surrounding musculature (43). Both forms of exercise should be used in rehabilitation and training programs to provide varying training stimuli, in terms of kinematic and kinetic profiles. Cam and lever resistance may also be beneficial as a supplement to weight-bearing exercises in programs for osteoporotic and osteoarthritic populations, as it may provide a safe-controlled form of resistance that would help improve bone density and limit deterioration according to the stress–strain relationship between load and bone density (19,51,65). Some of the aforementioned benefits also are considered limiting factors in the development of certain kinematic and kinetic variables, which are discussed in the following section.

Limitations of Cams and Levers. One major limitation is that the movement pattern of cam and lever equipment cannot be manipulated by the lifter to suit his/her mechanical and physiological needs; instead, the lifter is required to adapt to the equipment. During equipment design, torque changes through the various angles are based on sample averages (26,29). A problem arises in the fact that the equipment is designed for the average person and may not accommodate people that have extreme differences in anthropometry. Force-angle curves are affected by mechanical variables, such as limb length, point of tendon attachment, and velocity of movement (26). Attempts have been made to match the machines resistive torque curves to the 3 types of human strength curves; however, the efficacy of such an approach is debatable (11). For example, Harman (31) found that Nautilus
Various elastic resistance products.

The term elastic resistance can be misleading, since it does not fully describe the exact type of resistance that tubing, bungies, and bands provide. That is, all of these products are viscoelastic, exhibiting nonlinear or viscous properties in combination with linear elastic properties. This can be observed in the diagram below comparing the tension and deformation of various sized rubber bands (Figure 7). The nonlinear curves observed can be best fitted with second order polynomials, rather than simple linear functions (64). For a detailed discussion of viscoelasticity please refer to any good biomechanical text.

As can be observed from Figure 7, there is a relatively linear-elastic region that can be explained using Hooke’s law if the resistive forces need to be quantified. That is the tension provided by the RBR is equal to the stiffness constant (k) multiplied by the deformation (d):

\[ Tension = k \times \text{stiffness} \times \text{deformation} \]

During the elastic region, deformation increases in direct proportion to the amount of tension placed on the RBR product, and this linear relationship can exist for deformations of up to 300% depending on the composition of the product (4,28).

The Hygenic Corporation was the first major producer and distributor of RBR training products and currently has 7 resistance levels on the market, ranging from 1.5 to 10.75 Newtons in tension at twice the bands resting length (53,61). Today there are a number of manufacturers that make a variety of bands with different tensile properties. RBR tension can also be increased by shortening the resting length or by increasing the number of bands (7). The various rubber band tensions and elongation percentages (changes in deformation) are depicted in Figure 8 (53). RBR products were initially designed for rehabilitating and restoring muscle and joint functions; today, they also are used for improving conditioning and balance and building strength in all individuals (61).

The way in which tension of RBR is delivered is dependent on the setup of the apparatus (64). RBR can be set up to increase or decrease the resistive load during the ascent phase of a lift and decrease or increase the resistive load during the descent phase. Deformation-tension curves of RBR are closely related to the ascending strength curve; therefore, RBR should theoretically supplement ascending strength curve exercises. The equipment can also be set up to help athletes overcome the initial sticking point in the bench press and the squat, i.e., RBR can be attached to the bar and/or athlete to offer a degree of unloading.
For this to occur, the bands are attached to the top of a power rack, to provide assistance when the active muscles in movements, such as the bench press and squat, are at maximal lengths, where the mechanical advantage is least.

Kinematics and Kinetics of RBR. RBR is proportional to the amount of deformation multiplied by the stiffness constant during the elastic region of the deformation–tension curve. Rubber bands allow for variable resisted movement in a multiple of planes, such as the sagittal, frontal, transverse, or a combination (oblique) of planes while maintaining consistent resistive properties in all planes, unlike gravity dependent modes. Most gravity-dependent modes of training (e.g., free weights and chains) offer the greatest amount of resistance with movements in the vertical (frontal and sagittal) plane only. A comparison between the direction of external resistance of RBR and free weights is shown in Figure 9. The curvilinear deformation–tension properties of RBR allow for increased acceleration in the initial, less-resisted positive phase of a lift; as a result, velocity of the exercise movement increases. During the ascent phase of an ascending strength curve lift, the musculoskeletal system gains a mechanical advantage and force production decreases (6,17,24,66). This area is one in which the added band tension has the potential to increase muscle stimulation, motor unit recruitment, and firing rates and in turn prevent a decrease in muscular force production throughout the last quarter of the lift (17). The use of RBR in training has been shown to increase strength in recreational athletes by 10–30% over 6- to 12-week training periods; however, similar gains also have been reported with most other modes of resistance when used properly; therefore, further research is needed to determine whether one mode is superior to the other (53).

A study by Damush and Damush (15) found that older adult women increased strength during an 8-week RBR training program. The program consisted of 2 training sessions per week. Seven 1-set exercises were performed at each session, each exercise was performed until a level of 4 was reached on the Borg Perceived Exertion Scale. The 7 exercises included seated lat. pulldown, seated single leg press, seated chest press, seated single toe press, standing tricep press, standing bicep curls, and seated leg extension. Strength improvements occurred in 3 major muscle groups; the latissimus dorsi (19.7 ± 10.3%), the quadriceps (27.7 ± 17.6%), and the pectoralis major (16.5 ± 11.2%); where the subjects 3 repetition maximums were measured on the seated lat pull down, seated leg extension, and seated chest press, respectively.

When bands are added to free weight exercises, such as the squat, dead-lift, and bench press, the added tension towards the end of the positive concentric phase may trigger an increase in muscular force generation and peak power production (64). Wallace et al. (64) reported increases in peak force (16%) and peak power (24%) were
greater during the back squat when rubber bands were used in combination with free weights compared with the use of free weights only. These variables (peak force and peak power) were recorded at a frequency of 500 Hz using a Quattro Jump force plate and assessed with Quattro software. It may be speculated that RBR allowed the lower-extremity muscles of the subjects to produce greater peak force at the position where the mechanical advantage of the segment lever system was greatest (near full extension) due to the curvilinear tensile properties of RBR and ascending strength curve properties of the squat. Another study by Cronin et al. (14) compared the kinematics, kinetics, and EMG of ballistic squats with and without rubber bungies and a nonballistic squat; all movements were performed with a supine squat machine. They found that when loads were equated that there was greater EMG activity of the vastus lateralis during the eccentric contraction of the rubber bungie supine squat, and greater peak velocities were found for both ballistic squats (14). Improvements in peak velocity, force, and power in the lower extremities may be beneficial to athletes participating in contact sports, such as rugby, all disciplines of football, ice hockey, as well explosive track and field events (sprinting, shot putt, hammer throw, high jump and long jump).

In summary, the addition of RBR to a constant external resisted movement alters the biomechanical profiles, as RBR products allow for greater accelerations to be produced in the initial phases of a movement compared to a constant external resisted movement with an equivalent load. However, the force required to elicit movement will increase proportionally with the displacement and changing deformation–tension of the RBR; and the greatest forces will be required at maximal displacement or end range of movement. Thereafter, greater accelerations occur earlier in the eccentric phase, which should result in increased eccentric forces and potentially greater SSC enhancement. It has been suggested that the benefits of RBR are most apparent when combined with free weights, so that the inherent shortcomings of either resistance type compensate for one another (7,64). That is, free weights provide greatest mechanical overload at the beginning or inner range of the concentric phase and the bands provide overload at the end or outer range of the concentric phase for ascending strength curve movements. The opposite is true of the eccentric phase in terms of the mechanical overload; therefore, the combination of both resistance modes may compliment each other throughout the entire concentric and eccentric phases for most multi-joint movements.

Practical Applications of RBR. RBR is prescribed and used in many rehabilitation programs because it is a portable and a relatively inexpensive low-impact, momentum-controlled resistance used for multiplanar training unaffected by gravitational forces. It also promotes neuromuscular coordination and stabilization, which are all important factors in postinjury rehabilitation (52). RBR training may be used to benefit many different components of the musculoskeletal system, including increases in muscle mass, power and endurance, decreased body fat, and improved balance, gait, and mobility (53). Exercises performed in the transverse plane would benefit from RBR because the resistance supplied by the rubber bands is collinear to the movement. Rotator cuff rehabilitation programs use rubber bands for this very reason, as internal and external rotations about the shoulder are performed in the transverse plane. Many baseball pitchers use RBR training after reconstructive surgery of torn rotator cuffs initially to increase strength of the internal and external rotators and to the increase range of motion about the glenohumeral joint (47,54,63). Rehabilitation programs that use RBR training include stroke patients, osteoarthritic patients, elderly populations, contracture patients, and other pathological groups. Through supplemented RBR training programs, stroke, osteoarthritic, and elderly patients have demonstrated improvements in strength, gait, balance, and function, leading to improved quality of life and the prevention of falls (13,41,50,52,55). Manor et al. (44) also found that rubber bands were a valid and reliable means to assess upper extremity strength in older adults. It is inferred that RBR training can be used effectively in exercises with ascending strength curves because of the
similarities between the deformation–tension relationship of RBR and the force–joint angle relationship of an ascending strength curve. When combining bands with free weights, it is recommended that RBR comprises 20–35% of the total resistance and free weights comprise the remaining 65–80%, with a total load of 60% or 80–85% of the athletes’ 1-repetition maximum (1RM) to improve peak power and peak force outputs, respectively, for the back squat and possibly other ascending strength curve exercises (49,57,64). Anderson et al. (1) compared a free weight training group to a combined training group (free-weight plus RBR) with similar baseline measurements. They found that supplemented RBR training improvements during the back squat and bench press were significantly greater than that of the free weight-only training group. 1RM performance was 3 times greater for the back squat (16.47 ± 5.67% kg vs. 6.84 ± 4.42% kg) and 2 times greater for the bench press (6.68 ± 3.41% kg vs. 3.34 ± 2.67% kg) with the supplemented RBR training (1). The back squat and bench press supplemented with RBR may be helpful in training athletes who could benefit from increased strength, average and peak power, and peak force, as found in studies by Anderson et al. (1) and Wallace et al. (64). These increases may translate into improvements in maximum strength, vertical jump, ballistic ability, and enhanced sport performance, but investigations have yet to fully demonstrate these adaptations.

RBR also can be used to magnify the stretch load and enhance the eccentric phase during plyometric training (see Figure 10). In this exercise, the athlete begins the movement with the RBR on stretch, which increases the acceleration and subsequent medio-lateral ground reaction forces to the athlete when they step inwards (14). RBR is also applied to other sport-specific training programs, including the various tennis strokes and catcher-specific movements in baseball, but there is no empirical evidence related to the efficacy of these programs (6,22). For the various tennis strokes, tubing may promote the development of speed and strength, an important combination in developing a superior tennis stroke. Initially, resistance in the tubing is low, allowing for an increase in limb velocity and, as the athlete moves through the range of motion, resistance progressively increases, providing overload to the involved musculature (6,7). If resistance is too low initially, dumbbells can be supplemented with rubber bands and tubing to provide an increase in resistance (7). For catchers, once the ball is caught, it is important to ascend quickly into the throwing position. This is done by exploding out of the squat position while simultaneously rotating the hips and feet into the correct throwing stance. A harness and RBR bands are attached to the athlete and as the athlete explodes out of the squat position resistance is increased, training the athlete to generate greater speed and power through the quadriceps, hamstrings, gluteals, hip, and torso musculature (22). It must be noted that adding RBR to sport-specific movements may change the natural coordination of the movement and result in performance decrement if used as the main source of resistance training; therefore, the use of RBR in combination with sport-specific free weight and body weight movements may prove to be the most beneficial form of training.

Limitations of RBR. The lack of research and scientific evidence to support the practical benefits of RBR is a major limitation to the efficacy of RBR training. Some clinicians think that the limitations of RBR training outweigh the benefits, such as the inability to quantify resistive load and prescribe specific loading patterns, due to the viscoelastic properties of rubber. It should also be noted that RBR products have stretch maximums known as yield and fracture points, where the rubber begins to break down and eventually fail, which may pose a problem for movements with significant displacements, such as the squat, standing shoulder press and push press (57).

It may be that the use of RBR is limited to a specific group of ascending strength curve exercises and may not be suitable for exercises with bell-shaped and descending strength curves because it could be detrimental to the development of strength and other kinematic and kinetic variables.
However, this is dependent upon the equipment set-up and goal of the movement. For example, because of contradicting deformation–tension relationship of RBR and the force–joint angle relationship of the musculoskeletal lever system, RBR may be inadequate for certain resistance training exercises, because the contracting muscle(s) would be improperly overloaded (22, 28, 46, 51). Wallace et al. (64) found that peak power during the back squat decreased by 13% using RBR at a substituted 35% of the total load when compared with RBR at 20%. Another study on the back squat by Ebben and Jensen (17) found no significant differences for integrated electromyography and mean ground reaction forces when using RBR at a substituted 10% of the total load compared to traditional constant external resistance squats.

Given these findings, it may be that supplemented RBR training is beneficial to a very narrow range of constant resistance loads on the loading spectrum. Future research should be conducted on measuring the kinematic and kinetic variables during varying intensities of RBR training for exercises with ascending strength curves. The long-term efficacy of RBR training on force and power output needs to be investigated and compared with other modes of resistance training. Also, charts converting or equating the deformation–tension relationships of RBR bands to mass in pounds and kilograms should be readily available to assist clinicians and practitioners in prescribing specific loading intensities (62).

**CHAINS**

Chain and RBR properties are similar in that resistance increases throughout the range of motion; however, one resistance type increases in a linear (chains) and the other in a curvilinear (RBR) fashion (Figure 11). The 2 forms differ in terms of their physical and mechanical properties; rubber bands are composed of hydrocarbon polymers and chains are composed of steel, which is a combination of iron and carbon. RBR is dependent on the stress–strain or deformation–tension relationship, whereas chain resistance is dependent on vertical displacement and gravitational force.

Chains can be added to free weights to vary the loading pattern (external resistance) and training stimulus. Chains, although an unconventional training technique, have become popular among some high-level power and weightlifters (12, 57). In a research study on chains, Coker et al. (12) observed that time of applied force, initial acceleration, and the recruitment and activity of stabilizing and synergist muscles are increased via chain training. Members of the powerlifting community also have used chains in their training because it is believed that this is an effective resistance mode for developing speed, acceleration, and absolute strength. However, little scientific evidence exists to support these claims, and future research is required to validate such contentions (57).

**Kinematics and Kinetics Chains.** Mechanically, adding chains to the ends of a barbell has a similar net effect as RBR in the vertical direction; as the bar moves upward, resistance progressively increases because the chains are lifted off the ground, and as the bar is lowered the resistance decreases (9). Chain structure, density, length, and diameter are determinants of chain weight and must be known to prescribe specific loading intensities. Berning et al. (9) developed charts matching chain link diameter and length to mass that could prove to be of practical benefit, as chain weight increases and decreases in proportion to the number of links that leave the floor. An example is displayed below in table form based on chain sets (two chains of equal diameter and length) (Table 2) (9). Chains should be a minimum of 2½ meters in length, as some powerlifting and weightlifting movements have a large range of bar displacements depending on the exercise–lift and height of the athlete-lifter. The additional chain length is needed because it is important to keep a portion of the chain in contact with the floor at all times to prevent injury and limit excessive oscillation and sway (9).

The weight of the chain is calculated by multiplying the mass (kg) of the chain links leaving the floor by gravity (~9.81 m/s²). Because of the gravitational dependent properties of chains, movements should be performed in the vertical plane for maximal chain resistance and optimal training benefits.

![Resistive curves of; (a) rubber-based resistance (5 different bands), and (b) chain resistance (5 different chain widths).](image)

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The multi-joint movements in powerlifting (e.g., bench press, deadlift, and squat) and specific phases (assistance lifts) of weightlifting (e.g., snatch, clean and jerk) have ascending strength curves and are performed primarily in the vertical planes (sagittal and frontal), as illustrated in Figure 12. With ascending strength curve exercises, the musculoskeletal system gains a mechanical advantage as the working muscles extend the involved joint segments. Variying the resistance throughout the lift alters the kinetic (e.g., force, work, and power) and kinematic (e.g., time, velocity, and acceleration) variables. Theoretically, adding chains to powerlifting movements and assistance lifts (e.g., first pull in the clean and snatch, and the jerk phase in the clean and jerk) in weightlifting with ascending strength curves, should allow for enhanced acceleration during the initial phase of the lift. At the base of the lift, the chains’ external resistance and human torque capabilities are low; and progressively increase throughout the range of motion to match the musculoskeletal system’s increased ability to produce force and create torque (9). During these multi-joint movements the musculoskeletal system’s ability to handle greater external forces (loads) increases as the involved joints extend and reach a position of single joint configuration i.e. the involved joints have reached full extension and the external load is applying a compressive force (65). It has been proposed that using chains with powerlifting and various assistant weightlifting movements may promote the development of power, acceleration, motor control, stabilization and enhanced neurological adaptation (9,12,27). In terms of power development, this makes sense, as there is an initial increase in movement velocity and latter increase in muscular force requirement, caused by the progressively increasing external resistive load of the chains. However, it should be remembered that most of the aforementioned claims are anecdotal.

**Practical Applications of Chains.** The use of chains alone and in combination with free weight training is becoming more frequently used by strength and conditioning practitioners as a method of training. It has been suggested that chains improve strength and power, extend the duration of the acceleration phase and subsequently increase velocity during the positive (concentric) phase of the lift (e.g., bench press). Whether this is actually true is yet to be determined and the reader needs to be cognizant of this limitation when reading the literature in this area. One practitioner suggested using a lighter free weight load (e.g., 90 kg) and attach additional chain resistance (e.g., 15 kg) to the bar, resulting in a total apex load greater than that of his or her maximum, due to the change (rise) in position of the sticking point for ascending strength curve movements. For example, if an athlete has a maximum bench press of 100 kg, he/she should be able to bench press a total load greater than that of his or her maximum, due to the change (rise) in position of the sticking point. One practitioner suggested using a lighter free weight load (e.g., 90 kg) and attach additional chain resistance (e.g., 15 kg) to the bar, resulting in a total apex load greater than the athletes 1RM (105 kg), possibly leading to increases in maximal strength (17,57). As for optimal gains in power, another practitioner suggested that a lighter total resistance between 60 to 90 % of the athletes 1RM be used, with 80–85% of the percentage load coming from free weight resistance and 15–20% from chains; as this changes the kinetics of a strength exercise into a power exercise allowing for greater acceleration throughout the range of motion (5). All of these practical benefits may potentially lead to a stronger more explosive

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Length (cm)</th>
<th>Chain mass, length and diameter</th>
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</thead>
<tbody>
<tr>
<td>Mm</td>
<td>Inches</td>
<td>Mass (kg)</td>
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<tr>
<td>6.4</td>
<td>¼</td>
<td>0.3 0.6 1.3 2.8 2.5 5.5 3.8 8.3 5.0 11.0</td>
</tr>
<tr>
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<td>3/8</td>
<td>0.4 0.8 1.9 4.1 3.7 8.1 5.6 12.2 7.4 16.3</td>
</tr>
<tr>
<td>12.7</td>
<td>½</td>
<td>0.7 1.6 3.7 8.1 7.4 16.3 11.1 24.4 14.8 32.6</td>
</tr>
<tr>
<td>19.1</td>
<td>¾</td>
<td>1.4 3.1 7.0 15.4 14.0 30.8 21.0 46.2 28.0 61.6</td>
</tr>
<tr>
<td>22.2</td>
<td>7/8</td>
<td>2.2 4.8 10.8 23.8 21.6 47.5 32.4 71.3 43.2 95.0</td>
</tr>
<tr>
<td>25.4</td>
<td>1</td>
<td>2.8 6.2 14.0 30.8 28.0 61.6 42.0 92.4 56.0 123.0</td>
</tr>
</tbody>
</table>

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athlete and could possibly be applied to sport specific training programs. Athletes who must overcome large external resistances (e.g., American football, rugby, wrestling, and mixed martial arts) may benefit from strength and power training programs supplemented with chains.

Chains may be a useful supplement to free-weight resistance in that they add a variable training stimulus to a training program, which would be otherwise unavailable (57). The oscillating chains provide a predictable, but varying movement path, as a result of the applied force. Practitioners claim that the oscillating chains may promote improved motor control, increased activation and recruitment of stabilizing and synergist muscles, and enhanced neurological adaptation; but these claims are not scientifically supported and may merely be a result of performing free weight resistance (9,12). It may be speculated that chains offer a changing external resistance proportional to the mechanical advantage gained by the musculoskeletal lever system as the joints extend and flex throughout positive-concentric and negative-eccentric phases. However, the benefits of training with chains are not well documented and current claims lack scientific support; therefore, some of the contentions must be viewed with caution.

Limitations of Chains. One distinct limitation in chain training is the lack of scientific research performed in this area; most claims are anecdotal and until conclusive evidence is presented, the proposed benefits remain hypothetical. Two studies, one by Coker et al. (12) and the other by Berning et al. (8), found that lifting with chains versus lifting without chains did not cause any changes in the kinematic and kinetic variables of the lifter during the snatch; which may have been due to the a low chain load (5% of the total load) used. In addition, only a limited number of kinematic and kinetic variables were measured in these studies, none of which truly reflected the technique of the lifters, giving sports scientists another reason to be skeptical of chain training. There is limited information on the relationship between chain diameter and length to weight ratios (9). The length, diameter, and density of the chain, as well as the selected exercise, segment length, and height of the lifter, dictates how much weight the lifter will be moving throughout the range of motion (9). All of these factors must be taken into consideration when calculating the exact load of the corresponding chain. In this process, the chance of calculation error would increase as the number of factors considered increases. The average external chain load and length to weight ratios over the entire range of motion should be measured and calculated to allow practitioners to prescribe specific and precise loading patterns for the desired lift and individual. These measures need to be validated and published in a standardized chart, as none currently exist. The following measures should be included; chain diameter to weight ratios and chain length to weight ratios ranging from 1 to 250 centimeters in length as the ranges in displacements (range of motion) vary largely from exercise to exercise.

In terms of the strength curves, because chain weight increases in a positive

Figure 12. The deadlift supplemented with chains, illustrating a collinear movement with respect to gravity.
linear fashion, exercises with descending and bell-shaped strength curves may not be properly overloaded with chains. For optimal benefits, chain training may be limited to ascending strength curve exercises. The gap between scientific data and anecdotal claims is a clear indication that future research is required if chains are to become a valid mode of training for enhancing power, strength and athletic performance (12).

CONCLUSION
After reviewing the different forms of VR training, we hope that a better understanding and appreciation of the kinematics and kinetics, practical applications, and limitations has been acquired. Cam and lever systems are designed to accommodate exercises with ascending, descending and bell-shaped strength curves purportedly enabling greater specificity in terms of overloading the working muscles, but there is contradictory evidence in the literature. The systems resistive torque is designed to match human torque capabilities, increasing resistance at points where strength is greatest and decreasing the resistance at points where the strength is lowest; but again there is much debate over the validity and effectiveness of cam and lever systems as a mode of resistance training. Cams and levers also are used widely in the rehabilitation setting to correct muscle imbalances and certain pathologies; where single joint-designed machines allow clients to isolate a specific group of muscles. A major limitation to cam and lever systems is that the movement must travel a fixed path and may not accommodate for the biomechanical and physiological variations of the individual. A fixed movement path may also hinder development of intramuscular and intermuscular coordination. Even with these limitations, cam and lever systems can still be utilized effectively in resistance training programs.

RBR is viscoelastic and its tension is determined by its stiffness properties, where its curvilinear deformation-tension relationship is better fitted by a second order polynomial, rather than a first order-linear function polynomial, as rubber is not purely elastic. RBR may be used in a multiple of planes (e.g. sagittal, frontal, transverse, and oblique), as the resistance is collinear to and directly opposes most exercise movements. For this reason, RBR is used widely in the rehabilitation setting for many pathologies (e.g., contractures, patellofemoral pain, stroke, elderly, and osteoarthritis) and sport specific training (e.g. sprint, rotator cuff rehabilitation, racket sports). RBR provides a low-load resistance for initial rehabilitation, and when used in conjunction with constant external resistance, it can gradually and progressively increase strength in weak atrophied muscles. RBR used in combination with free weight resistance has been beneficial in improving various kinematic and kinetic variables over a narrow range of loading intensities. Limitations arise, as RBR has viscoelastic properties where tension increases in a curvilinear fashion and may not compensate exercises with descending and bell-shaped strength curves. The lack of scientific support for RBR training and the limited research quantifying its viscoelastic properties (deformation-tension relationship), provides further constraints to RBR training, hence the need for future research.

Chain resistance increases linearly with displacement and can be represented by a basic linear function (first order polynomial), as chain resistance is gravity dependent and determined by the density, diameter and length of the chain; therefore, chain resistance would appear best suited for training exercises with ascending strength curves, such as the squat, dead-lift, bench press and shoulder press. Various reputed practitioners have claimed improvements in the kinematic and kinetic variables of the lifter, as well as increased activation of stabilizing muscles and enhanced neurological adaptations; but a lack of scientific evidence has led many to be skeptical of chain training. Limitations to chain training also include the lack of standardization in regards to the type and quality of steel used for resistance training. Another inherent limitation is that chain weight to displacement ratios have not been properly quantified over a large displacement range.

Future biomechanical research is required in the area of VR training modes, in order to bridge the gap between the practitioner and scientist. Ariel (3) once said that “the equipment should adapt to the user rather than the user adapt to the equipment.” Following along with this line of logic when implementing resistance training programs, the kinematic and kinetic profiles associated with the various modes of resistance should be considered and prescribed appropriately to match the varying human strength curves and mechanical advantage of the different musculoskeletal lever systems; as well as the sport and athlete specific training goals (2,3).
REFERENCES


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