BIOMECHANICAL BASIS OF STRENGTH TRAINING

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The objective of this lecture is to systematize and convey biomechanical knowledge to athletic practitioners, specifically coaches .

By definition, strength, or muscular strength, is the ability to exert maximal external force.

Three main problems exist in strength conditioning for qualified athletes:

1. Exercise selection - which exercises should be used by the athlete;
2. Training load, in particular training intensity and volume; and
3. Training timing, i.e. the distribution of the exercises and load over the time periods.

The problem of the exercise selection only, in particular its biomechanical aspects, is covered in this lecture.

EXERCISE SPECIFICITY. As adaptations effects are specific, the exercises employed in training need to correspond with the main sport exercise. The degree of this correspondence, or similarity, is called *specificity* of the training exercise. The specificity of training directly reflects its efficiency and deserves thoughtful attention by the coach. A main tendency in the modern training of elite athletes is the increased percentage of specific exercises. Contemporary sport training is, in general, more specific than training in the past.

In various sports, exercise specificity is determined by different factors. In strength and power sports, the movement coordination, in the broad sense of this term, is scrutinized.

Main sport exercises with additional resistance

Requirements for the exercise specificity are best met when the main sport movement, with increased (added) resistance, is used for training.

Resistance in athletic events can be increased in various ways.

(a) A d d i t i o n a l w e i g h t. Implements of heavier weight such as weight vests, belts, hand cuffs, ankle cuffs, etc. may be worn. While this approach is simple, it should be noted that the demand for the vertical force (acting against gravity) principally increases with supplementary weight. Exercising with additional weight requires that force is exerted in an inappropriate direction, i.e.too vertically.

(b) U p h i l l a m b u l a t i o n (running, walking, skiing, etc). This practice is limited by the possible changes in sport technique.

(c) R e t a r d i n g t h e a t h l e t e ' s p r o g r e s s i o n; for example, running with a harness, towing a sled, or a pulley machine with a weight stack. These methods are cumbersome in that the equipment is bulky and heavy.

(d) I n c r e a s e d a e r o d y n a m i c r e s i s t a n c e. This method is very popular among elite athletes in sports such as speed skating, running, and others. Small parachutes are used for this purpose. When the athlete runs, the parachute inflates, which creates a drag force. The higher the running velocity, the greater the resistance force.

Assistance exercises

A variety of strength exercises, beyond the main sport exercise, are used in the training routines of athletes. The selection of strength exercises for qualified athletes is substantially more complex than it is for beginners. The general idea is simple: strength exercises must be *specific*. This means that training drills must be relevant to the demands of the event for which an athlete is being trained. However, the practical realization of this general idea is not easy The main requirements of such a task are described as follows.

(A) WORKING MUSCLES.

This requirement is most evident and simple: the same muscle groups must be involved in the main sport event and in the training drill. For instance, heavy resistance exercises for the improvement of the paddle stroke in canoeing should focus on those muscles and their motion patterns associated with the paddling.

Three techniques are employed to identify the working muscle groups:

i. Muscle palpation. Muscles that become tense are the 'involved' muscles and they should be trained with heavy resistance.

ii. Intentional inducing of delayed muscle soreness, i.e. the pain and soreness that occurs 24 to 48 hours after training workouts. With this aim in mind, a coach intentionally overdoses the training load during the first workout with newly practiced drills. The painful muscles then are determined to be working muscles.

iii. Registering muscle electric activity (EMG). This method is superior, however special equipment and technical personal are needed for such analysis.

(B) TIME (and RATE) OF FORCE DEVELOPMENT.

It takes time to develop maximal force in a given motion. The time to peak force (T_m) varies with each person and with different motions; on the average, it is more than 0.3-0.4 seconds. This time for maximal force development is compared below with the typical time of several motions performed by elite athletes:

Motion	Time (s)
Take-off	
sprint running	0.08-0.10
long jump	0.11-0.12
high jump	0.18
Delivery	
javelin	0.16-0.18
shot put	0.15-0.18
Hand take-off	
horse vaulting	0.18-0.21

It is easy to see that the time of motion is less than T_m in all examples given. Because of their short durations, the maximal possible force F_{mm} cannot be attained in these motions. The difference between F_m (the maximal force reached in a given condition) and F_{mm} (the highest among the maximal forces attained in the whole range of the tested conditions) is the greater, the lower the resistance and shorter the motion time. The difference between F_{mm} and F_m is appropriately termed the explosive strength deficit(ESD) By definition:

$$ESD\ (\%) = 100 * (F_{mm} - F_m) / F_{mm} \quad (1)$$

ESD shows the magnitude of an athlete's strength potential that <u>was not used</u> in a given attempt. In movements such as take-offs and delivery phases in throwing, ESD is roughly about 50%. For instance, among the best shot putters during throws of 21.0 m, the peak force F_m applied to the shot is in the range 50-60 kg. Their best results in arm extension (F_{mm}, bench press) is typically around 220-240 kg, or 110-120 kg per each arm. Thus, they can use, in throwing, about 50% of F_{mm} only.

When sport performance improves, the time of motion turns out to be shorter. The better an athlete's qualifications, the greater the role of the rate of force development in the achievement of high level performance.

By definition, explosive strength is the ability to exert maximal forces in minimal time. Several indices are used to estimate explosive strength and the rate of force development. There are:

(a) Indices of explosive strength (IES)

$$IES = F_{max}/T_{max}, \qquad (2)$$

where F_{max} is the peak force and T_{max} is the time to peak force .

(b) Reactivity coefficient (RC)

$$RC = F_{max}/T_{max} * W, \quad (3)$$

where W is an athlete's weight (or weight of an implement). RC is typically highly correlated with jumping performances, especially with body velocity after a take-off.

(c) Force gradient, also called S-gradient ('S' for 'Start")

$$S\text{-gradient} = F_{0.5} / T_{0.5}, \qquad (4)$$

where $F_{0.5}$ is one half of the maximal force F_m and $T_{0.5}$ is the time to attain it. S-gradient characterizes the rate of force development at the beginning phase of a muscular effort.

(d) A-gradient ('A' for 'Acceleration")

$$A\text{-gradient} = F_{0.5}/(T_{max} - T_{0.5}) \qquad (5)$$

A-gradient is used to qualify the rate of force development in the late stages of explosive muscular efforts.

F_m and the rate of force development, in particular S-gradient, are not correlated. Strong people do not necessarily possess a high rate of force development.

Due to the existence of the *explosive strength deficit*, maximal force F_{mm} cannot be attained in the *time deficit zone* when the time of the motion is short. If the objective of the training is to increase maximal force production, F_{mm}, there is no reason to use exercises in the time deficit zone, where F_{mm} cannot be developed. In turn, heavy resistance exercises are not a very useful training tool for enhancing the rate of force development in qualified athletes.

If the general objective of training is to increase force production in explosive types of movement, it can, in principle, be done in either one of two ways:

(a) To increase maximal force F_{mm}. This strategy of training, however, brings good results only when the explosive strength deficit is much less than 50%.

(b) To increase the rate of force development. Heavy resistance exercises are not the best choice in this instance especially for elite athletes. Special exercises and training methods are recommended with this purpose.

(C) TYPE OF RESISTANCE.

Force is the measure of the action of one body against another, and its magnitude depends on the features and movements of both bodies in action. The force exerted by an athlete on an external body (i.e. a free weight, a throwing implement, the handle of an exercise machine, water in swimming and rowing, etc) depends not only on the athlete but on external factors as well.

To judge the role of external resistance with respect to its worth, imagine an athlete who exerts maximal force (F_m) in a leg extension such as squatting. Two experimental paradigms are employed. In the first case, the maximal isometric force (F_m) corresponding to different degrees of leg extension is measured. According to the results of many investigations, the correlation between the force F_m and leg 'length' (i.e. the distance from the pelvis to the foot) is positive: if the leg extends the force increases (Figure 1, curve A). *Maximum maximorum* force (F_{mm}) is achieved when the leg's position is close to the extended one. This is in agreement with everyday observations: the heaviest weight can be lifted in semisquatting, not deep squatting movements.

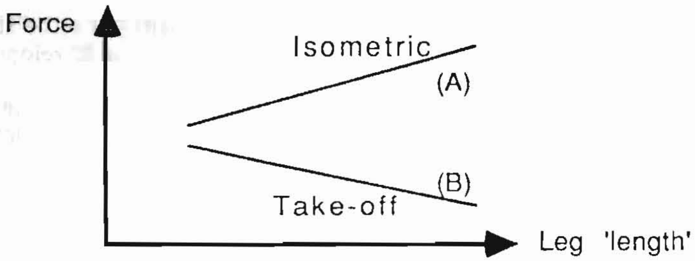

Figure 1. Relation between maximal force in leg extension and body position (leg's 'length'). A scheme.
A - isometric testing; B - take-off

However, if the force of leg extension is registered in a dynamic movement such as a take-off in jumping the dependence is exactly opposite (Figure 1, curve B): maximal force is achieved in the deepest squatting position. The correlation of F_m to leg length, then, is negative. The mechanical behavior of a support leg resembles, in this case, the behavior of a spring: the greater the deformation (i. e. knee bending) the greater the force. Note that in both experimental conditions, isometric and jumping take-off, the athlete's efforts for attaining the best possible achievements are maximal. Thus, both the magnitude of F_m and the correlation of F_m to leg length (positive or negative) are changed due to alterations in the type of resistance.

Due to the requirements for specificity of strength exercises, the selection of the proper class of mechanical resistance equipment is important in training. The following types of resistance classes are typically employed in resistance training programs:

Elasticity. The magnitude of force is determined by the range of displacement.

Mass. A movement follows Newton's second law of motion: the force is proportional to the mass (inertia) of the accelerated body and its acceleration.

Weight. The formula is $F= W+ma$, where W is the weight of the object, m is its mass, and a is acceleration.

Viscosity. With training devices of this type, the exerted muscular force is proportional to the movement velocity, $F=kV$.

Hydrodynamic resistance. Force depends on the velocity squared: $F=kV^2$, where V is the velocity relative to water and k is a coefficient.

In terrestrial movements, the weight or/and the mass of an object (an implement, barbell, own body) usually serves as resistance. In aquatic sports, such as swimming, rowing, kayaking, canoeing, the resistance is determined by hydrodynamic principles. If training drill resistance is changed in comparison to the resistance in the sport event itself, for which the athlete is being trained, both force production and the pattern of muscle activity are altered.

(D). VELOCITY of movement.

Velocity of a motion decreases as the external resistance (load) increases. For instance, if an athlete throws shots of different weight, the throwing distance (and initial velocity of the implement) increases as shot weight decreases. Maximum force (F_{mm}) is attained when velocity is zero, or near zero; and, inversely, maximum velocity (V_{mm}) is attained when external resistance is zero. The external force, in this instance, is also zero.

Analogous experiments carried out on single muscles in laboratory conditions yield the well known force-velocity curve. Force-velocity relationships in human movements are not identical to analogous curves of single muscles, as they are a result of the superposition of the force outcome of several muscles possessing different features. In spite of that, force-velocity curves registered in athletic movements can be considered as hyperbolic. This approximation is not absolutely accurate, but the accuracy is acceptable for the practical problems of sport training. The ratio a/P_{mm} varies from 0.10 to 0.60. Athletes in power sports usually have a ratio higher than 0.30, while endurance athletes and beginners have a ratio that is lower.

The effect of strength exercise depends on the velocity of movement. If exercises are performed in the 'high force, low velocity' range of the force-velocity curve, the maximal force F_m increases mainly in the trained range. On the other hand, if the 'low force, high velocity' range is used in training, the performance is improved primarily in this area (Figire 2).

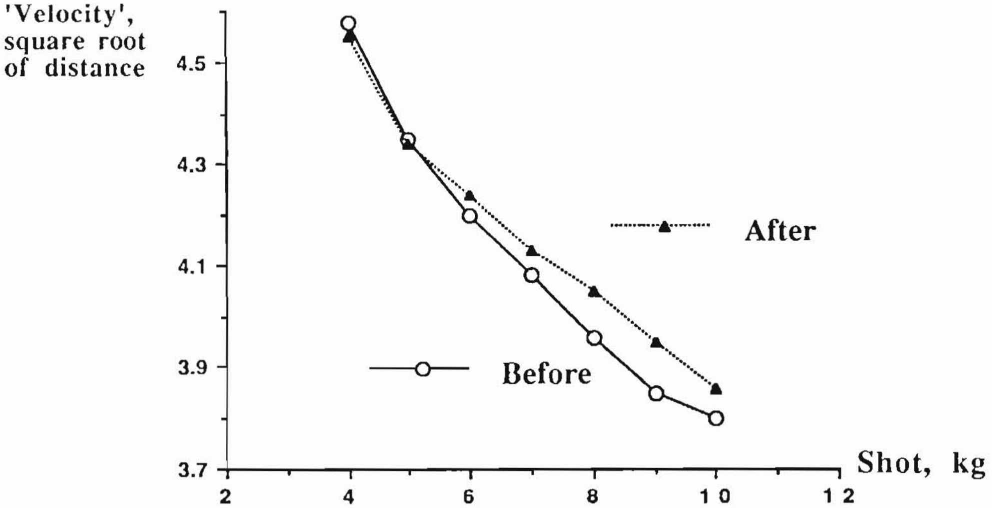

Figure 2. Performance results in standing shot putting before and after 7-week training with heavy shots (8-10 kg). The throwing routine comprized of puts heavy shots (70% of all the puts) and standard shot (7.257 kg, 30%). The shots from 4 to 10 kg were used for testing (Zatsiorsky & Karasiov, 1978).

These findings serve as a basis for the recommendation to develop force at speeds that approximate the athletic motion.

This is particularly true for relatively slow movements, such as those used during dry land training for aquatic sports, endurance sports, etc. However, if an exercise is performed in the 'low force, high velocity' range, the time available for movement may be too short to develop the maximal force F_{mm}. The aforedescribed situation with the training either F_{mm} or rate of force development occurs (see TIME OF FORCE DEVELOPMENT section). The practical solution is based on the recommendations:

i. to lift all weights with the maximum attainable velocity,

ii. for F_{mm} training - do not decrease the resistance too much,

iii. for dynamic strength training - choose the proper amount of the resistance so as to produce movement velocity in the same velocity range of the relevant sport event.

(E). FORCE - POSTURE RELATIONSHIP.

Certain relationships exist between body posture (i.e. joint angle) and the maximal strength that can be developed at this body position (called *human strength curves*). Maximal muscular strength varies over the full range of joint motion. The interplay of changes in both muscle lever arms and muscle force production determines this effect.

Three different approaches are used in contemporary strength training to manage the 'force-angle' paradigm (the fourth 'solution' is not pay attention to this issue at all). They are: 1. Peak-contraction principle, 2. Accommodating resistance, and 3. Accentuation.

1. Peak-contraction principle, is, historically, the oldest approach. The idea is to focus efforts on increasing muscle strength primarily at the weakest points of the 'human strength curve'. The peak-contraction principle is realized, if the 'worst comes to worst' - the external resistance (moment of gravity force) is maximal at the point where muscular strength is minimal. Practically, the peak-contraction principle is realized in one of three ways:

i. Selection of proper body position.

ii. Use of special training devices.

iii. The slow beginning motion in strength drills.,

2. Accommodating resistance. The main idea is to develop maximal tension throughout a complete range of motion rather than at a given (i.e. weakest) point. This can be achieved in two ways:

i. Offering high resistance without mechanical feedback. In this case, the speed of motion is constant no matter how much force is developed. This principle is realized in *isokinetic* equipment.

Isokinetic training, very popular in physical therapy, is rarely used by elite athletes. Besides the high cost of equipment, which may be prohibitive, it has additional shortcomings. The angular velocity of movement is typically below 300°/s (it may be above 5000 °/s in athletic movements). Most training devices are designed to perform exclusively one-joint movements which are used only sporadically in athletic training, etc.

ii. Offering variable resistance which is accommodated either to (i) human strength curve, or to (ii) movement speed.

3. Accentuation. The main idea is to train the strength just in the range of the main sport movement in which the demand for high force production is maximal.

(F). DIRECTION OF MOVEMENT.

(1) ECCENTRIC MUSCLE ACTION. Force in yielding phases of a motion, under conditions of imposed muscle lengthening (*eccentric* or *pliometric muscle action*), can be well over the maximal isometric strength of an athlete (up to 50-100%). This is essentially true for qualified athletes and in multi-joint motions, such as the leg extension (in untrained persons, maximal voluntary torque output during eccentric knee extension or flexion is independent of movement velocity and remains at an isometric level). The same holds true for isolated muscles: eccentric force for a single muscle may reach a level of up to twice the zero velocity (isometric) force.

Because exercises with eccentric muscle action necessarily involve high force development, the risk of injuries is high; a risk coaches should understand. Even if the eccentric force is not maximal, such exercises (i.e. as downhill running) may easily induce delayed muscle soreness, especially in unprepared athletes. The cause of the muscle soreness is damaged muscle fibers. This damage is often considered a normal precursor to muscle adaptation to increased use. Conditioning of the muscles reduces the amount of injury.

(2) REVERSIBLE MUSCLE ACTION. Many movements consist of eccentric (stretch) and concentric (shortening) phases. This stretch-shortening cycle is an element, quantum, of many sport skills and is referred to as the *reversible action* of muscles.

If a muscle shortens immediately after a stretch:

(a) force and power output increases, and

(b) energy expenditure decreases.

Thus, muscles can produce greater mechanical force and power, while utilizing less metabolic energy. Prestretching of active muscles is broadly used to enhance force (power, velocity) output in sport movements. The wind-up movement in throwing serves as an example.

Increased force is exerted in the shortening phase of a stretch-shortening cycle due to several reasons. At the peak of the cycle, i.e. at the moment of transition from lengthening to shortening, the force is developed in isometric conditions, thus the influence of high velocity is avoided, and F_{mm} rather than F_m is exerted. Since the force begins to rise in the eccentric phase, the time for force development is greater; counter-movement jumps (not drop jumps) are evidence of such an occurrence.

Apart from the aforementioned mechanisms, two groups of factors influencing the outcome of movements with reversible muscle action should be named: peripheral - muscle and tendon elasticity, and central (neural) - reflex action.

If a tendon or active muscle is stretched, the elastic energy is stored within these biological structures. This deformation energy is recoiled and used to enhance motor output in the concentric phase of the stretch-shortening cycle. According to physical principles, the magnitude of the stored energy is proportional to the applied force and the induced deformation. Since the muscle and the tendon are arranged in series, they are both subjected to the same force, and the distribution of the stored energy between them is, in this case, only a function of their deformation. The deformation, in turn, is a function of muscle or tendon *stiffness* (or its inverse value - *compliance*).

The stiffness of a tendon is constant, while the stiffness of muscles is variable and depends on the forces exerted. The passive muscle is compliant: it can be easily stretched. The active muscle is stiff: one must apply a great force to stretch it. The greater the muscle tension, the greater its stiffness. Superior athletes can develop high forces. The stiffness of their muscles, while active, exceeds the stiffness of the tendons. That is why elastic energy in elite athletes, for instance during take-offs, is stored primarily in tendons rather than in muscles. Tendon elasticity and a specific skill of using this elasticity in sport movement (take-off, delivery, etc.) is important for elite athletes.

Consider the neural mechanisms governing reversible muscle action during landing in drop jumps.

After foot strike, there is a rapid change, both in the length of active muscles, and in the force they develop. The muscles are forcibly stretched, and at the same time, there is a sharp rise in muscle tension. These changes are controlled and partially counterbalanced by the concerted action of two motor reflexes: *myotatic* (or *stretch*) *reflex* and *Golgi tendon reflex*

These reflexes constitute two feedback systems that operate:

(a) to keep the muscle close to a preset length (myotatic reflex; *length feedback*),

(b) to prevent unusually high and potentially damaging muscle tension (Golgi tendon reflex; *force feedback*).

The efferent discharge to the muscle during the stretching phase of a stretch-shortening cycle is modified by the superimposed effects of two aforementioned reflexes: positive (excitatory) - from myotatic reflex, and negative (inhibitory) - from Golgi tendon reflex. During landing, a stretch applied to a leg extensor produces (via myotatic reflex) a contraction in that muscle; simultaneously, a high muscle tension sets up a Golgi tendon reflex in the same muscle, thus inhibiting its activity .

If athletes, even strong ones, are not accustomed to such exercises, the activity of the extensor muscles during take-off is inhibited by Golgi tendon reflex. Because of that, even the world class weight lifters cannot compete with triple jumpers in drop jumping. As a result of specific training, the Golgi tendon reflex is inhibited, and the athlete sustains very high landing forces without a decrease in exerted muscular force. The dropping height may then be increased.

In beginners, performance in exercises with reversible muscle action may be improved as a by-product of other exercises such as heavy weight lifting. In qualified athletes, this skill is very specific. Performances, in drop jumps for example, are not improved as a result of 'usual' strength exercise, even with heavy weights. Maximal muscular strength (F_{mm}) and forces produced in fast reversible muscle action (F_m) are not correlated in good athletes. They should be treated, and trained, as separate motor abilities.

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