Strength is Specific

By Chris Beardsley

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DEDICATIONS

By Chris Beardsley

Rather than ask someone to write a foreword, I decided to use this opportunity to say thanks to a few people.

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1. WHY “JUST GET STRONG” IS WRONG!
Imagine you coach a track and field team. You have sprinters running 100 – 400m, middle distance athletes running 800 – 1,500m, and maybe even long distance athletes running >5km. Or imagine working with swimmers (four strokes over multiple distances), rowers, triathletes, or cyclists.

As a good coach, you would likely put time into learning about programming for each endurance sport.

Each of your programs would center around the main activity (running, swimming, cycling, etc.), and it would be specific to the athletes’ goals in terms of both intensity and distance.

Now, after putting in all that work, how would you feel if one of your colleagues ignored your programs, and kept saying: it doesn’t matter, just get fit.

I don’t know about you, but I would be very annoyed!

After all, we know that fitness is specific to the type of training you do.

**Why “just get strong” is wrong!**

Just like fitness, strength gains are specific to the type of training that you do.

Instinctively, we know that this is true for fitness. A great marathon runner will never be a great rower. And a great swimmer will never be a great cyclist.

But while we all pay lip service to the idea that strength is specific (we can all repeat the Specific Adaptation to Imposed Demands (SAID) acronym), many strength coaches do not really believe it.

If we really believed it, then we would not say “just get strong” whenever someone asks a question about how to program resistance training for sport. We would look more carefully at the demands of the sport first.

In other words, “just get strong” is wrong because strength is specific.
How is strength specific?

This ebook works through a series of chapters showing how strength is specific. Work through them, and you will learn that strength gains are greater when tested with the same muscle action, velocity, range of motion, external load type, and degree of stability as are used in training.

So if you want to improve your ability to decelerate, eccentric training is better than concentric training. To improve force production at high speeds, high-velocity is better than low-velocity training. To get strong over partial ranges of motion, partials are better than full range of motion exercises. To get strong against a constant load, train with a constant load. To get strong in unstable environments, training under those conditions gets you stronger than a more stable set-up.

Maximizing the effectiveness of a strength training program means designing it to fit the specific goal you want to achieve. In other words, using the right tool for the job.

How much difference does specificity make?

You might be tempted to think that the specificity effect of strength training is just a small detail. It is not. It is huge.

Compare the effects of training with eccentric vs. concentric muscle actions. Using elbow flexion exercise, Vikne et al. (2006) showed that gains in eccentric 1RM after eccentric training were more than twice as large as those after concentric training.

Or compare training with partial vs. full ranges of motion (ROM). When partials do improve full ROM strength, it is never as much as full ROM training. On the other hand, they usually produce much larger gains in partial ROM strength (Bloomquist et al. 2012).

Or compare the effects of training under different stability conditions, by looking at strength gains after training on machines that use fixed bar paths or on machines that use cables to allow freedom of movement (Cacchio et al. 2008). The same thing applies. Sure, you can get stronger in all strength tests that use the same movement pattern with any type of training. But if you use the exact same type of training, then your strength gains will be much, much greater.

Get strong for the right movement, not the wrong one.
Why are strength gains specific?

Many people get confused about the relationship between muscle size and strength, and this leads them to swing from one extreme to another.

On the one hand, there are those who seem to think that muscular size and strength have little connection with each other. On the other hand, there are plenty of fitness writers these days who will argue that strength is almost entirely a function of size.

The truth is that although muscle size is the single most important predictor of strength, it does not exclude other factors also having an impact. In a recent important study exploring what makes some people stronger than others, the inter-individual variance in muscle strength predicted by muscular size was around 55%.

So to be clear, muscle size is the most important predictor of strength.

That still leaves 45% unexplained, though!

The remainder of the difference is probably accounted for by many different peripheral and central factors (not just neural ones, like you might read in an old textbook). These include:

- Muscle fascicle length
- Muscle pennation angle
- Moment arm length
- Single fiber characteristics
- Extracellular matrix features
- Neural drive to the agonists
- Co-activation of antagonists

Why am I talking about this?

These features are what make strength gains specific.
References


2. MUSCLE ACTION
In the last decade or so there has been a surge of interest in eccentric training, which is training solely using the lowering phase of an exercise. Much of this excitement surrounds the use of eccentric training for preventing or rehabilitating injuries. Even so, a key point is that strength gains after eccentric training are muscle-action specific. They are greatest when measured with an eccentric test.

This is not surprising, as specificity of strength gains is one of the fundamental principles of strength training. Specificity can be observed to varying degrees in relation to load, speed, range of motion, and external resistance type, as well as muscle action.

But why does it happen after eccentric training?

**What do "eccentric" and "concentric" training mean?**

When you lower a weight, it involves lengthening the prime mover muscles. This is called the eccentric phase. When you lift a weight, it involves shortening the prime mover muscles. This is called the concentric phase.

It is that simple, really.

Normal strength training comprises both lowering and lifting weights. This means both lengthening and shortening muscles under tension, usually directly in sequence. This sequence is called the stretch-shortening cycle (SSC).

Using solely the eccentric phase is very common in rehabilitation, but there are also reasons why it might help enhance sports performance, for reasons I will explain shortly. Using solely the concentric phase is rarer, but does occur naturally as a result of the way in which some exercises are performed (such as the weightlifting derivatives, loaded carries, and sled pushing or dragging).

Many literature review articles have been published about the unique properties of eccentric training (e.g. Brughelli & Cronin, 2007; Roig et al. 2009; Butterfield, 2012; Isner-Horobeti et al. 2013; Herzog, 2014; Vogt & Hoppeler, 2014; Kjaer & Heinemeier, 2014; Gluchowski et al. 2015; Duchateau & Enoka, 2016). There are also a number of good practical guides to eccentric training (e.g. Mike et a. 2015).

What can I say? It is a popular topic.
How do shortening and lengthening contractions differ?

To understand why eccentric training might produce specific strength gains, it is helpful to start with how shortening and lengthening contractions differ at the most basic (myofibrillar) level.

From a biomechanical point of view, muscles are structured of both active and passive elements. Importantly, the passive element has elastic properties. However, when performed from a standing start (and ignoring the role of titin for a moment), shortening contractions can only make use of the active element.

Muscle shortening is driven (almost) entirely by chemical energy being converted into kinetic energy within individual sarcomeres, which make up the myofibrils inside the single fibers of a muscle. The thin (actin) and thick (myosin) myofilaments of the sarcomeres slide past one another, in a crossbridge cycle. The myosin myofilament drives this process, by detaching from actin, releasing ADP and rebinding with ATP, and binding to actin again further along the myofilament (Månsson et al. 2015).

In contrast, lengthening contractions make use of both active and passive elements. Also, the way in which the active element functions in lengthening contractions differs from the way it works in shortening contractions. In lengthening contractions, the myosin crossbridges of the active elements are forcibly broken, detaching the myosin head from actin, without release of ADP and subsequent rebinding of ATP (Månsson et al. 2015). This is part of the reason why the energy requirement of lengthening contractions is quite low in comparison with shortening contractions.

In addition to the different way in which the active elements function during lengthening contractions, there is also a key role for passive elements: they resist lengthening. The passive elements include the three main extracellular matrix layers that surround the muscle fiber (the endomysium), the muscle fascicle (the perimysium), and the muscle itself (the epimysium), as well as the giant molecule titin, which lies parallel to the actin and myosin myofilaments.

Force production during muscle lengthening is therefore driven only partly by chemical energy being converted into kinetic energy within individual sarcomeres, as it is also partly supported by the elastic elements (Herzog, 2014).

This is a key point that differentiates lengthening and shortening contractions, and it has important implications.
What are the important implications?

When exerting the same external force, lengthening contractions require less input from the active elements that drive muscle contraction, and they also require less energy.

This translates to both lower neural drive (as measured by EMG), and a smaller metabolic cost in sub-maximal lengthening contractions compared to shortening contractions, for the same external force (Bigland-Ritchie & Woods, 1976; Duchateau & Enoka, 2016).

To put it another way, you experience sub-maximal lengthening contractions as being easier than comparable shortening contractions. This is because the passive elements contribute to the force production, which allows the active elements to have an easier ride.

Additionally, maximal force producing capability in lengthening contractions is definitively greater than in shortening contractions, despite what some strength coaches might claim. It is greater by around 50 – 80% when measuring single fibers in vitro, and by around 30 – 50% when measuring strength in live humans (Duchateau & Enoka, 2016).

Maximal force producing capability is greatest in lengthening contractions, because under these conditions both active and passive elements can be made to contribute to their full extent at the same time, and the sum is much greater than just the active elements on their own.

Does eccentric training display specific strength gains?

In one of the first studies to compare eccentric and concentric training, Komi & Buskirk (1972) reported that eccentric training improved eccentric strength more than concentric training did, while both eccentric and concentric training groups improved concentric and isometric strength tests similarly.

Many later studies have confirmed that gains in eccentric strength are greater after eccentric training than after concentric training (Higbie et al. 1996; Hortobágyi et al. 1996; 2000; Miller et al. 2006; Nickols-Richardson et al. 2007).

What does that look like?
Here is an example, taken from Nickols-Richardson et al. (2007):

And this is not just a newbie phenomenon. In fact, we can see exactly the same effects in resistance-trained individuals. For example, as reported in Vikne et al. (2006):

As you can see from the charts, concentric training also displays strength specificity, although the effect is much less marked.
You can also see that eccentric training benefits concentric strength more than the other way around.

The exact reasons for this are fairly obvious, but quite complex to explain. Put simply, titin is involved in displaying both eccentric strength and concentric strength, but the changes in titin that occur inside a muscle fiber are probably greater after eccentric training, than after concentric training.

(I will explain more about how titin is affected by eccentric training below.)

In the meantime, what we can say is that after either eccentric or concentric training, the ratios between eccentric and concentric strength, between eccentric and isometric strength, and between concentric and isometric strength are all changed (Hortobágyi et al. 1996; Vikne et al. 2006).

For example, in the study in trained subjects shown above, after elbow flexion training in resistance-trained subjects, the ratio of eccentric to concentric 1RM decreased from 1.30 to 1.20 after concentric training, but increased from 1.21 to 1.33 after eccentric training (Vikne et al. 2006).

So when we perform eccentric training, we are not just increasing strength, lengthening muscle fascicles, or altering injury risk, we are also altering the ratio of how much force we can produce while decelerating, compared to how much force we can produce while accelerating.

(This has important injury prevention implications. I will not say any more about it here, because I want to cover it properly in a later section.)

But why does this ratio change?
Why are strength gains after eccentric training specific?

So why are the gains in eccentric strength after eccentric training so much larger than gains in other forms of strength?

Although it has been extensively discussed whether eccentric training is superior to concentric training for hypertrophy (Roig et al. 2009), the answer probably lies in some of the other adaptations that occur after strength training, as hypertrophy should affect strength gains in all contraction modes in a relatively similar way.

Indeed, some of these changes in other features of the musculoskeletal system are very pronounced after eccentric training, while others are more obvious after concentric training. Some of the key changes are:

- Muscle architecture
- Muscle fiber type
- Regional hypertrophy
- Extracellular matrix and cytoskeleton
- Tendon stiffness
- Neural adaptations

Let’s take a look at each of these in turn.
#1. Muscle architecture

Strength training produces alterations in muscle architecture (muscle fascicle length and pennation angle), and these alterations differ in size depending on whether the contraction type used is predominantly eccentric or concentric.

Muscle fascicle length seems to increase by more after eccentric training, compared to after concentric training (Ema et al. 2016). Such changes probably occur through an increase in the number of sarcomeres in series within the myofibrils of a muscle fiber (Brughelli & Cronin, 2007; Butterfield, 2012).

These increases may have advantages for fast movements, as longer fascicle lengths likely allow superior contraction velocities since all the sarcomeres in a myofibril contract at the same time. They also seem to increase the joint angle for force production (to longer muscle lengths), which could be beneficial in some cases (Brughelli & Cronin, 2007). On the other hand, developing longer muscle fascicles seems to be bad for RFD, as longer fibers require more time to go from slack to taut at the onset of a muscle contraction (Blazevich et al. 2009).

Since changing muscle fascicle length is essentially an increase in muscle size (Wisdom et al. 2015) it is hard to determine the effects on strength, in isolation from hypertrophy. But the emphasis on increasing muscle fascicle length rather than pennation angle may be beneficial, in comparison with concentric training.

Indeed, muscle pennation angle seems to increase by more after concentric training, than after eccentric training (Ema et al. 2016). Increases in muscle pennation angle seem to be mainly a way to accommodate increases in muscle size, by packing more muscle tissue into the same space (Fukunaga et al. 1996), and since the angle of force production becomes less advantageous with increasing pennation angle, this involves a trade-off between more muscle tissue and a smaller component of force.

In any event, without a lot of extra analysis, there seems to be no obvious reason at the moment to assume that the different changes in muscle architecture (muscle fascicle length vs. pennation angle) are responsible for the specificity of strength gains after eccentric training.
#2. Muscle fiber type

One common suggestion is that eccentric training can produce greater, or preferential, type II muscle fiber area growth than concentric training.

Indeed, there are some indications that this may be the case (Hortobágyi et al. 1996; Hortobágyi et al. 2000; Friedmann-Bette et al. 2010). But there are also an equal number of contrary reports that should make us pause before jumping on this idea (Mayhew et al. 1995; Seger et al. 1998; Vikne et al. 2006).

One explanation for this apparent phenomenon (assuming it is true) is that the size principle is breached, and eccentric training produces earlier recruitment of high threshold motor units, which are believed to correspond to type II muscle fibers (McHugh et al. 2002).

This explanation has two key flaws.

Firstly, a review of studies using careful methods has shown that the size principle is almost certainly not breached during eccentric training (Chalmers, 2008).

Secondly, although not widely-appreciated, the high threshold motor units that are recruited under situations of high demand do not actually correspond directly to type II muscle fibers anyway (Enoka & Duchateau, 2015).

Given the very conflicting evidence for preferential fiber type development from eccentric training compared to concentric training or SSC exercise, on top of the lack of a plausible mechanism, the jury is definitely out on whether this is a mechanism by which eccentric training could produce greater gains in strength.

Therefore, there is no obvious reason to assume that different rates of growth in muscle fibers of differing fiber types underpins the specificity of strength gains after eccentric training.
#3. Regional hypertrophy

Regional hypertrophy is a normal aspect of resistance training, and has been observed after various different programs, and in many muscles.

Even so, it has been argued that eccentric training might be particularly effective at producing regional hypertrophy, which is where certain parts of a muscle are more extensively developed than others (Hedayatpour & Falla, 2012). A large portion of the argument put forward here is dependent upon muscle fiber type differences and differences in their activation between lengthening and shortening contractions, which is an assumption that has recently been strongly challenged (see above).

Moreover, in the small number of studies that have actually compared the impact on regional hypertrophy between concentric and eccentric training, there have been no differences between the two training types (Smith & Rutherford, 1995; Blazevich et al. 2007).

So it seems very likely that regional hypertrophy does not differ between concentric and eccentric training, and therefore that this phenomenon is not responsible for the specificity of strength gains after eccentric training.
#4. Extracellular matrix and cytoskeletal adaptations

Around muscle fascicles, and around muscles themselves is an extracellular matrix made of different types of collagen (the three main layers are called the epimysium, the perimysium, and the endomysium).

Within each muscle fiber are myofibrils, supported by scaffolding-type structure, called the cytoskeleton. This cytoskeleton has longitudinal (parallel) and transverse (perpendicular) elements, and the most important longitudinal element is titin.

The amount of collagen within a muscle can increase as a result of exercise (Kjaer, 2004; Wisdom et al. 2015). While this is a bad thing for cattle breeders selling meat, it is usually a good thing for athletes. Collagen itself is very stiff and adding more collagen around the myofibrils increases the stiffness of the individual muscle fibers (Gillies & Lieber, 2011). This probably contributes to enhanced force production during lengthening contractions.

Similarly, the structure and content of the cytoskeleton within a muscle fiber can increase with training. Titin in particular seems to be affected. The number of titin filaments that surround each myosin filament can increase from 3 to 5 with training (Hidalgo et al. 2014; Krüger & Kötter, 2016). This almost certainly improves force generation during lengthening contractions (Lindstedt et al. 2001).

Eccentric exercise is particularly good at damaging both the extracellular matrix and the cytoskeleton, including titin (Friden & Lieber, 2001), and it triggers cellular signaling processes that interact with titin (Krüger & Kötter, 2016). This is almost certainly because eccentric training naturally relies more on these passive elements during contractions, and this greater loading in turn leads to more damage. Therefore, it is logical that eccentric exercise might produce greater adaptations in the passive elements than concentric training.

Unfortunately, very little work has been done to compare the effects of eccentric and concentric training types on adaptations in the extracellular matrix, the cytoskeleton, or titin (except for about a million studies looking at muscle damage).

Even so, it seems like a fairly safe bet that the specific gains in eccentric strength that are observed after programs of eccentric training are caused at least partly by changes in the extracellular matrix, in the cytoskeleton, and in titin.
#5. Tendon stiffness, and muscle stiffness

Stiffness is the extent to which an object resists being lengthened. A stiff spring only lengthens a little when you attach a weight to it. On the other hand, a compliant spring lengthens quite a long way.

Muscle-tendon units have both muscles and tendons in series (one after the other). So while we can look at the overall stiffness of the whole muscle-tendon unit, we can also assess the individual stiffness of both the muscle and tendon, separately.

Strength training leads to increased tendon stiffness, and although the effects are affected by load (higher loads are better), they do not differ between eccentric and concentric training (Bohm et al. 2015).

In contrast, while muscle stiffness probably increases slightly after concentric training, most likely because of increases in extracellular matrix and titin content (Gillies & Lieber, 2011) more recent research suggests that it actually decreases after eccentric training (Kay et al. 2016).

This seems strange.

If anything, we might expect that increases in muscle stiffness should be superior after eccentric training. Indeed, older research in animals using accentuated eccentric training, such as downhill running, has reported contrary results (Lindstedt et al. 2001). One possible explanation for this discrepancy could be the large increases in fascicle length that are produced by eccentric-only training.

Stiffness is stress (force per unit area) divided by strain (relative length change). So applying a stress to a long muscle fiber will result in a larger relative length change than the same stress applied to a shorter muscle fiber, all other things being equal.

Consequently, increasing muscle fascicle length will lead to you recording a lower value of stiffness, even if the individual muscle fibers are themselves now made of stiffer material. What this means is that while muscle-tendon stiffness often increases with normal strength training or with concentric exercise, it does not necessarily increase after eccentric exercise (Kay et al. 2016). Increased muscle-tendon stiffness probably translates to greater joint stiffness, which could be desirable or not, depending on the goals of the athletes (Brazier et al. 2014).
Ultimately, what we can say is that since changes in tendon stiffness do not seem to differ between concentric and eccentric training, changes in tendon stiffness are not responsible for the specificity of strength gains after eccentric training. The changes in muscle stiffness are less clear, but this might be because they are produced by a combination of variables.

#6. Neural adaptations

Over 20 years ago, a case was made that the neural control of lengthening contractions was different from shortening contractions, such that high threshold motor units were recruited earlier (Enoka, 1996). This would be in contradiction of the size principle.

More recently, this proposal was confirmed as rejected, and it is now believed that the size principle is maintained in both lengthening and shortening contractions (Duchateau & Enoka, 2016).

However, that does not mean that other aspects of neural control (that do not violate the size principle) cannot differ between lengthening and shortening contractions.

So it is interesting to observe that after programs of unilateral exercise, eccentric training produces a greater cross-over of strength gains from the trained limb to the untrained limb than concentric training (Hortobágyi et al. 1997; Seger et al. 1998; Nickols-Richardson et al. 2007; Kidgell et al. 2015). Kidgell et al. (2015) suggested that this occurs because of greater reductions in corticospinal inhibition following eccentric training, compared to after concentric training.

Consequently, it seems probable that the specific gains in eccentric strength that are observed after programs of eccentric training are caused at least partly by different neural changes, including greater reductions in corticospinal inhibition.
Conclusions

Lengthening contractions involve lower metabolic cost, and require lower neural drive than shortening contractions for the same external force production. Maximal eccentric force is around 30 – 50% greater than maximal concentric force, and could be even higher in athletes.

Compared to concentric training, eccentric training seems to produce greater increases in muscle fascicle length, greater increases in the stiffness of passive structures (extracellular matrix and titin), and greater reductions in corticospinal inhibition.

The specific gains in eccentric strength observed after programs of eccentric training are probably caused by increased extracellular matrix and titin content, which increase passive force production, and by elevated corticospinal excitability. Fiber type, regional hypertrophy, tendon stiffness, and muscle architecture seem to be less important.
References


3. VELOCITY
For developing the ability to produce force at high speeds, most coaches make use of ballistic exercises that involve moving quickly under load, like jump squats and Olympic weightlifting derivatives.

On the other hand, when asked, many people will tell you it is the intention to move quickly that makes athletes stronger at high speeds. But if that was true, then ballistic training would be unnecessary, and everything could be accomplished purely through standard, heavy resistance training.

So are strength gains velocity-specific or not?

Here is one way to look at it.

**What does "velocity specific" strength gains mean?**

For velocity-specific strength gains to occur, we need to see the largest gains in strength when we test force production at the same movement speed as we use in training.

So, if we train using a fast speed, we should see the greatest gains in strength when we test strength at a high velocity, and the smallest gains in strength when we test at a low velocity.

Similarly, if we train using a slow speed, we should see the greatest gains in strength when we test strength at a low velocity, and the smallest gains in strength when we test at a high velocity.

In practice, of course, we are most interested in whether we can produce greater gains in strength at high velocities, by training using fast bar speeds.

It is that simple.
Why is velocity-specificity so complicated, then?

Figuring out velocity-specificity gets complicated quickly, because there are two ways in which you can alter the speed you are moving a weight.

Firstly, you can simply add plates to the bar. That will slow you down even if you are using maximal effort for both the light and heavy loads, because of the force-velocity relationship. You cannot move heavy loads as quickly as light loads, it is just not possible.

Secondly, you can alter your intent towards how you perform the rep. You can choose to perform it with maximal effort, or you can perform it with sub-maximal effort.

Which approach you choose has different implications. The best way to understand this is to appreciate that the force you exert on a barbell is made up of two parts: weight (force due to gravity) and inertia (force required to accelerate mass).

If you take the first approach, and add plates to the bar to reduce your speed, you will increase weight, because the extra plates are heavier, but you will decrease inertia slightly, because you cannot accelerate a heavy barbell as quickly (although its mass is greater). The net effect is to increase total force.

If you take the second approach, and keep the same plates on the bar but deliberately use a controlled tempo to reduce your speed, the weight stays the same, but you will decrease inertia, because you have chosen to accelerate the barbell more slowly. The net effect is obviously to decrease total force (Bentley et al. 2010).

In the first approach, force and velocity are matched to the underlying abilities of the muscle, while in the second, force is lower than it could be.

So far, so good?
Does changing the weight on the bar produce velocity-specific strength gains?

If the weight on the bar produces velocity-specific gains in strength, then we should find that training with low forces (and therefore light weights) produces greater strength gains at faster speeds than when using high forces (and therefore heavy weights).

Essentially, we should get something roughly like the following picture, when low-velocity and high-velocity groups test their strength at the same speeds, before and after programs of strength training:

![Graph showing force vs. velocity for low- and high-velocity training groups before and after training](image)

But does this really happen?

Many researchers have explored this question, going back nearly 50 years.

In fact, they have usually found velocity-specific results after isokinetic strength training when comparing two or more groups, where one group used a slow angular velocity, and the other a fast angular velocity, but both groups exerted maximal effort.

Typically, higher velocity training leads to greater gains in strength when tested at high isokinetic velocities (Moffroid & Whipple, 1970; Caiozzo et al. 1981; Coyle et al. 1981; Jenkins et al. 1984; Garnica, 1986; Thomeé et al. 1987; Petersen et al. 1989; Bell et al. 1989; Ewing Jr et al. 1990), although not always (Farthing & Chilibeck, 2003).
The velocity-specific effect of training with different loads is less consistently observed when using free weights, but is still apparent.

Interestingly, there tends to be a clearer velocity-specific pattern when the subjects use single-joint exercises (Kaneko et al. 1983; Aaagaard et al. 1994; 1996; Moss et al. 1997; Ingebrigtsen et al. 2009), than when they use multi-joint exercises (Almåsbakk & Hoff, 1996; McBride et al. 2002; Mora-Custodio et al. 2016).

There are a couple of reasons why this might be the case, but I will save that analysis for another section.
Does changing intention also produce velocity-specific strength gains?

It is quite hard to figure out whether intent produces velocity-specific strength gains.

Sure, it is easy to find studies showing that groups training using free weights with maximal speeds tend to experience greater strength gains measured at high velocities compared with similar groups that train at sub-maximal speeds (Jones et al. 1999; Morrissey et al. 1998; Ingebrigtsen et al. 2009; González-Badillo et al. 2014).

The problem with this approach is that it does not measure intent alone. It measures both intent and actual muscle contraction velocity.

So to be certain, researchers have isolated the effects of intent by controlling velocity. They do this by setting velocity to zero, which means isometric contractions.

In reality, muscle contraction velocity can only be mostly controlled for in isometric contractions. Isometric contractions involve some muscle shortening, even when the joint angle does not change.

When a muscle contracts, it shortens, even during isometric contractions, but the tendon lengthens so that there is no net change in the length of the total muscle-tendon unit. So the velocity is not zero, and the muscle shortens more with increasing force production (Narici et al. 1996).

Even so, training with maximal speed-intent and sub-maximal speed-intent isometric contractions do in fact produce different results, with maximal speed-intent training leading to greater gains in higher-velocity strength measures (Tillin et al. 2012b; Tillin & Folland, 2014; Balshaw et al. 2016).
So is intent the only factor driving velocity-specific strength gains? (part 1)

In perhaps the most famous velocity-specificity study, Behm & Sale (1993) tasked subjects to perform ankle dorsiflexion training using two methods (isometric and isokinetic), where both conditions required the subjects to "move as rapidly as possible regardless of the imposed resistance."

The isometric training was performed with maximal speed-intent but without moving, while the isokinetic training was performed with maximal speed-intent, and at a relatively high angular velocity (300 degrees/s).

Strength was tested at a range of angular velocities (0 – 300 degrees/s). However, there was no difference between the two groups in respect of the changes in strength at any velocity. Both training programs displayed velocity-specific strength gains, but there were no differences between them.

So does that mean the case is closed?

Well, perhaps not.

Although I can see why this important study was set up as it was, there are a couple of limitations that make me pause.

Firstly, it used a within-subject design, where one leg was trained using the isometric training program, and the other used the isokinetic training program. This leaves us at risk of a cross-over effect of specific strength gains from one limb to the other. Secondly, the joint angle of peak contraction differed between muscles, as both started at 30 degrees of plantar flexion, but the isokinetic training program had to accelerate without load until it reached the target velocity.

The study also reported a couple of unexpected results.

Normally, isometric training produces large increases in maximal isometric force (Del Balso & Cafarelli, 2007). Even when the intent is explosive, gains in maximum isometric force are usually seen (Maffiuletti & Martin, 2001; Tillin et al. 2012b; Tillin & Folland, 2014; Balshaw et al. 2016). But even though 500ms was allowed for each contraction (meaning that maximum force was reached), Behm & Sale (1993) reported at least one outcome where there was a reduction in maximum isometric force after training.
Also, gains in maximum isometric force after training with isometric contractions are usually much bigger than the gains in maximum isometric force after dynamic contractions (Jones et al. 1987; Folland et al. 2005). However, Behm & Sale (1993) reported no differences between the two conditions.

So ultimately, intent is probably not the only factor driving velocity-specificity.

**So is intent the only factor driving velocity-specific strength gains? (part 2)**

Just to be clear, I think that velocity-specific strength gains do happen in response to actual contraction speed, as well as in response to intent, for two main reasons.

Firstly, the subjects in almost all of the isokinetic studies that I referenced above were provided with instructions to perform repetitions with "maximal effort" or something along those lines, and yet there was still velocity-specificity when training with different loads.

Secondly, and probably more importantly in practice, we see that there is also evidence of velocity-specific gains in strength after resistance training or ballistic training with free weights, again when all repetitions (using either high or low loads) are performed with maximal effort (Moss et al. 1997; Ingebrigtsen et al. 2009).

So both actual velocity and intent are probably important.
Why are gains in strength velocity-specific? (part 1)

So having settled that velocity-specific strength gains probably happen both in response to actual movement velocity and the intent to move quickly, what is responsible for the adaptation anyway?

Well, in theory muscles can either increase their rate of force development, or increase their maximal contraction velocity while producing a certain level of tension (or they can do both at the same time). The following diagram shows the two possible adaptations.

![Diagram showing two possible adaptations of force development and strength.]

As you can see, within this model, the point in time where you measure force impacts whether you will expect to observe an increase or decrease in force expressed at high velocities after training.

If you measure force in the early phase (say around 100ms), while force is still rising (e.g. Tillin & Folland, 2014), then you will see a change in force only if rate of force development has increased. On the other hand, if you measure force in the late phase (say around 300ms), after force has reached its peak (e.g. Behm & Sale, 1993), then you will see a change in peak force only if force production at high velocities has altered.
Life, however, is not as simple as this theoretical model, and there are two complications.

Firstly, it is widely accepted that the motor program for explosive contractions is preprogrammed (Duchateau & Hainaut, 2008). Once triggered, it goes all the way through to the end before you get to stop running it. So many types of explosive or ballistic training may well develop both rate of force development and high-velocity strength at the same time.

Secondly, contraction type affects how quickly we reach peak force. Although it is widely accepted that peak force is only reached after around 250 – 300ms, the reality is that this only applies to isometric and eccentric contractions. Peak force in concentric contractions is reached in <150ms (Tillin et al. 2012a). So high-velocity strength may be more relevant than rate of force development in concentric contractions, than in isometric and eccentric contractions.

So in conclusion, velocity-specificity can theoretically happen by either increasing rate of force development or by improving force production at a maximal speed. Whether you measure force in the early or late phases of an explosive movement might affect what result you get from your strength test.
Why are gains in strength velocity-specific? (part 2)

There are many factors that could cause velocity-specific gains in strength. Here are some of the primary candidates:

- Muscle architecture
- Muscle fiber type
- Tendon stiffness
- Specific fiber velocity
- Neural adaptations

We can try to figure out whether each of these factors change in different ways after either velocity-focused (i.e. either high-velocity ballistic movements or explosive isometric contractions) or force-focused (i.e. either high-force strength training or sustained isometric contractions).

We can also look at whether they are theoretically more likely to produce early phase (rate of force development) or late phase (high velocity strength) effects.
#1. Muscle architecture

Strength training of all types, including both velocity-focused and force-focused approaches, alters muscle architecture (fascicle length, pennation angle, and cross-sectional area).

Increases in fascicle length could be helpful for increasing high-velocity strength, as longer fascicle lengths mean higher contraction velocities (Wickiewicz et al. 1984). This is because all the sarcomeres in a myofibril contract at the same time, meaning that a greater total change in length happens in the same time period.

On the other hand, longer fascicle lengths seem to lead to reduced rate of force development, as longer fibers require more time to go from slack to taut, at the onset of a muscle contraction (Blazevich et al. 2009).

So there may be a trade-off in the effects of increasing fascicle length, with early phase effects being disadvantageous and late phase effects being advantageous.

Even so, there are indications that fascicle length might increase by more after velocity-focused training, than after force-focused training (Blazevich et al. 2003; Alegre et al. 2006), suggesting that it may be a helpful adaptation in the overall mix of changes that occur.

Increases in cross-sectional area are helpful for increasing high-velocity strength, as larger, stronger fascicles can produce more force. This shifts the whole force-velocity curve upwards, making it easier to produce force at a given velocity.

When training for hypertrophy, low loads may produce similar gains in cross-sectional area to high loads, although this may require training to muscular failure (Schoenfeld et al. 2014).

When developing speed, sets with light loads are not taken to failure, and will likely not develop size to the same extent. This suggests that changes in cross-sectional area are not responsible for velocity-specificity.
Muscle pennation angle is much less easy to get a handle on than muscle fascicle length. Although increases in pennation angle mean a reduction in muscle fascicle length, this does not mean that muscle contraction velocity necessarily reduces.

Pennated muscle fascicles actually rotate during contractions, which reduces the effective pennation angle (Brainerd & Azizi, 2005), and the amount of rotation is greater in faster contractions (Azizi et al. 2008). This fiber rotation allows the muscle to achieve a faster contraction velocity than the contraction velocity of the individual muscle fibers within it, thereby negating the disadvantage that is associated with the pennation.

Even so, there are indications that pennation angle increases by more after force-focused training than after velocity-focused training (Blazevich et al. 2003; Alegre et al. 2006), although this is probably just because pennation angle changes tend to track changes in muscle size.

So to summarize, increasing muscle fascicle length might reduce rate of force development but it might also increase maximal contraction velocity. Changes in cross-sectional area and pennation angle are unlikely to contribute to velocity-specificity.
#2. Muscle fiber type

Velocity-focused training might be able to produce shifts in muscle fiber type (measured either by MHC composition or fiber type distribution) or preferential muscle fiber type area hypertrophy, in the direction of type I ⇒ type IIA ⇒ type IIX.

This could contribute to velocity-specificity, as muscle fibers do contract faster in the order type IIX > type IIA > type I (e.g. Trappe et al. 2006; Harber & Trappe, 2008).

Some studies have reported velocity-specific strength gains in conjunction with shifts in muscle fiber type or in fiber type distribution (Liu et al. 2003; Zaras et al. 2013), but most have found no changes in fiber type distribution, while still reporting velocity-specific strength gains (Coyle et al. 1981; Thomeé et al. 1987; Ewing Jr et al. 1990; Malisoux et al. 2006; Vissing et al. 2008).

And while there are indications of preferential increases in type II muscle fiber type area after training at faster speeds (Coyle et al. 1981; Thomeé et al. 1987; Zaras et al. 2013), this is also by no means a uniform finding (Ewing Jr et al. 1990; Malisoux et al. 2006; Vissing et al. 2008; Lamas et al. 2012).

This might be because of a trade-off in the effects of changing fiber type, with early phase effects being disadvantageous and late phase effects being advantageous.

Maximal force production is affected by muscle size, and changes in muscle size occur more in type IIA fibers, in parallel with a reduction in the proportion of type IIX fibers. So we might expect there to be a trade-off in early phase velocity-specificity and late phase velocity-specificity, because the loss of type IIX reduces rate of force development in the early phase, and gains in type IIA increase rate of force development and force production in the late phase.

This is more or less what we find, although the research is fairly limited.

For example, Häkkinen et al. (2003) found an increase in rate of force development over early and late phases combined (500ms), while type IIX fiber area reduced, and type IIA fiber area increased. Aagaard et al. (2010) reported no increase in rate of force development in the early phase (<250ms) but instead reported an increase in the late phase (at 250ms), again while type IIX fiber area reduced and type IIA fiber area increased.
More interestingly, Farup et al. (2014) found that the strength of the relationship between rate of force development and type IIX muscle fiber relative area reduced steadily as the time period moved further away from the onset of the contraction ($r = 0.61, 0.56, 0.46, 0.26$ for 30ms, 50ms, 100ms and 200ms). And Andersen et al. (2010) reported that the reductions in type IIX muscle fiber relative area after training were related ($r = 0.61$) to changes in rate of force development in the early phase (100ms) but not in the late phase (200ms).

So changes in fiber type (fiber, distribution, and relative area) may produce both decreases and increases in velocity-specific strength gains, depending on what time period you measure strength over, but velocity-focused and force-focused training do not seem to produce different effects (Malisoux et al. 2006; Vissing et al. 2008).

To summarize, different speeds of training do not seem to affect changes in muscle fiber type, but the effects of fiber type after any kind of training could differ, depending on the time period over which you measure force.
#3. Tendon stiffness

Stiffness is the extent to which an object resists being lengthened. A stiff spring only lengthens a little when you attach a weight to it. On the other hand, a compliant spring lengthens quite a long way.

Stiffer springs have greater rates of force development when included in a system, because they transmit forces quickly from one end to the other. More compliant springs have smaller rates of force development, so they absorb some of the energy before transmitting it to the system.

Strength training leads to increased tendon stiffness (Bohm et al. 2015) and it also leads to increased rate of force development (Blazevich, 2012).

The effects of strength training are affected by load, in that higher loads produce greater increases in tendon stiffness (Bohm et al. 2015), and strength levels are related to tendon properties (Muraoka et al. 2005). Since some researchers have proposed that heavier loads might produce superior gains in rate of force development to lighter loads (Blazevich, 2012), increased tendon stiffness might be the mechanism by which this adaptation occurs.

To summarize, increasing tendon stiffness likely increases rate of force development, but is more likely to happen in response to force-focused, and not velocity-focused training. It is therefore unlikely to contribute to velocity-specificity after high-velocity training.
#4. Single fiber velocity

Given that muscle architecture, muscle fiber type, and tendon stiffness are poor candidates for velocity-specificity, it is worth reminding ourselves that there must be some changes inherent inside a muscle that contribute to greater gains in force at higher speeds after velocity-focused training.

In their famous study, Duchateau & Hainaut (1984) compared force-focused and velocity-focused training and reported greater gains in maximum strength after force-focused training (20% vs. 11%), but maximal shortening velocity only improved after velocity-focused training (by 21%). Moreover, this maximal shortening velocity was measured in involuntary contractions, implying that peripheral factors must be involved.

One peripheral factor that we should not forget is the contractile properties of single muscle fibers.

In a remarkable study, Malisoux et al. (2006) assessed the effects of long-term plyometric training. They found that single fiber velocity increased in each muscle fiber type, by 18% in type I muscle fibers, by 29% in type IIA muscle fibers, and by 22% in type IIX muscle fibers. Although single fiber force also increased, this was caused by an increase in the cross-sectional area, and single fiber force normalized to cross-sectional area did not alter.

Previous studies in standard heavy resistance training reported increases in single fiber force, but not single fiber velocity (Widrick et al. 2002), suggesting that perhaps one way in which velocity-focused training produces velocity-specificity is by altering contractile components of the individual muscle fibers.

To summarize, single fiber contraction velocity can be increased by velocity-focused training, implying that velocity-specificity might be attributed to altered contractile components of the individual muscle fibers.
#5. Neural adaptations

There are three main ways in which neural adaptations might occur that produce velocity-specific strength gains: changes in agonist muscle drive at different time points, changes in co-activation, and changes in co-ordination.

Agonist neural drive is the signal from the brain to the muscle that makes it contract. It is a composite signal, made up of both motor unit recruitment (how many motor units are switched on), and motor unit firing frequency (how often they are activated each second). We can only measure neural drive indirectly, and we do it in two ways: voluntary activation (the difference between voluntary and involuntary force), and EMG amplitude (the electrical voltage recorded inside the muscle).

Overall, EMG amplitude during maximum voluntary isometric contractions does not appear to be altered differently after high-force or high-force-intent training, compared to after high-velocity or explosive-intent training (Lamas et al. 2012; Tillin & Folland, 2014; Balshaw et al. 2016). However, the EMG amplitudes at different points within the contraction do seem to be affected. Explosive training produces greater gains in early phase EMG amplitude, while maximal strength training produces bigger increases in the overall mean EMG amplitude during the whole contraction.

So there is definitely some sort of change in agonist neural drive strategy going on, with explosive training causing a shift towards a more "pulsed" effect, that peaks higher and then drops away.

Increased co-activation is thought to reduce performance, although it may be helpful for joint stabilization. Reducing co-activation is therefore one way in which strength can be increased, and it does seem to change with training (Tillin et al. 2011), although how much it contributes to increased force production is less clear.

If co-activation can be observed specifically after velocity-focused, rather than after force-focused training, then it could contribute to velocity-specific changes in strength. And there are some hints in this direction.
Indeed, Pousson et al. (1999) found that co-activation reduced only when tested isokinetically at the same velocity used in training, when using a high velocity. Geertsen et al. (2008) also reported evidence of suppressed co-activation during isometric contractions, after velocity-focused training. And Arabatzi & Kellis (2012) found that standard resistance training produced an increase in knee muscle co-activation during vertical jumping, while Olympic weightlifting produced no change, or even a slight reduction.

Changes in co-ordination can affect how much gains in more basic physical qualities (such as force production or rate of force development) are able to contribute to strength expressed at a certain speed.

In a short review, Blazevich (2012) noted that studies were less likely to report increases in rate of force development after strength training when the test exercise was not performed in the training period. So displaying gains in rate of force development that have been achieved during training in a subsequent, different exercise may require practice in the test exercise.

This is similar to the idea that using gains in force production achieved in training in vertical jumping requires practice in vertical jumping once the strength has been gained (Bobbert & Van Soest, 1994).

This could be one reason why high-velocity exercises seem to transfer better to sporting performance than low-velocity exercises (Mora-Custodio et al. 2016). The faster exercises contain high-speed co-ordination elements that then transfer better to sporting movements than the slower exercises. This is not as far-fetched as it sounds, as the extent to which different muscles contribute to overall performance in most sporting movements differs with speed (Beardsley & Contreras, 2014).

To summarize, greater early phase neural drive (and increased rate of force development), more suppressed co-activation, and greater co-ordination might all be achievable with velocity-focused training, compared to force-focused training, suggesting that each could contribute to velocity-specificity.
Conclusions

Actual velocity and intent to move quickly can both independently cause velocity-specific gains in strength. Velocity specific gains in strength probably occur by means of increased rate of force development, and by gains in maximal contraction velocity.

The main candidates for velocity-specific effects after velocity-focused training are probably greater increases in muscle fascicle length, larger changes in single fiber velocity, greater increases in early phase neural drive, more suppressed co-activation, and bigger improvements in co-ordination, compared to force-focused training.

Ultimately, however, both velocity-focused and force-focused training can produce different adaptations that seem useful for improving the ability to produce force at high velocities. This is evidenced by the greater increases in cross-sectional area and tendon stiffness that are achievable using force-focused training.
References


4. RANGE OF MOTION
One of the things that frustrates me about training in a commercial gym is watching the tiny little knee bends that some people call squats.

Quite honestly, it is enough to make me want to go back to training at home.

After all, we know from the research that partial squats are not as effective as full squats for increasing lower body strength, not to mention being worse for leg development and athletic performance.

But why are partial squats less effective?

Here is what I think is going on.

**What is a partial exercise?**

When talking about partial range of motion exercises, we tend to mean "just performing the top part of the available range of motion". In practice, this refers to exercise variations like board presses and half squats.

While it is possible to perform just the bottom part of the available range of motion, it is much less common. For example, you might perform a deadlift until the bar passed your knees (called a "halting deadlift") and then return it to the ground without completing the movement.

However, as we will see, since muscle length is the main driver behind why partial range of motion exercises produce partial results, this partial exercise variation is a completely different animal from a "normal" partial exercise, so I am going to ignore it for today.
Partial vs. full range of motion exercises

We can summarize how partial and full range of motion exercises differ very quickly.


When partials do improve full range of motion strength, it is almost never as much as full range of motion training (Massey et al. 2005; Hartmann et al. 2012; Bloomquist et al. 2013), albeit with some exceptions (Graves et al. 1992; Massey et al. 2004; Steele et al. 2012; Cale'-Benzoor et al. 2014).

More importantly, partial range of motion exercises display joint angle-specific gains in strength, with the strength gains being greatest around the trained joint angle (Graves et al. 1989; 1992; Barak et al. 2004; McMahon et al. 2014).

Also, the angle of peak torque moves to shorter muscle lengths (McMahon et al. 2014).

Full range of motion exercises tend to make you stronger at doing full range of motion exercises (Hartmann et al. 2012; Bloomquist et al. 2013; McMahon et al. 2014) and this type of training also usually transfers quite well to partial range of motion strength (Weiss et al. 2000; Hartmann et al. 2012; Bloomquist et al. 2013; McMahon et al. 2014), although usually not quite as well as training with partials.

Why does this happen?

Well, to explain why partial training produces greater strength gains in partial exercises, while full range of motion training produces greater strength gains in full range of motion exercises, we need to know how our strength differs across the joint angle range of motion, and we also need to know how our strength at different joint angles changes after strength training.

Let's look first at why we are stronger at some joint angles, compared others.
**Why are we stronger at some joint angles than others?**

We are generally stronger at some joint angles than others. In fact, there is usually one joint angle where we are much stronger than at all the other joint angles. This joint angle is called the angle of peak torque, and it can change after strength training.

This is important for understanding how strength changes at different joint angles. After all, even if we get stronger overall, if the angle of peak torque changes, then we will find that some joint angles increase hugely in strength, while others do not improve strength very much at all.

Many factors determine the angle of peak torque, including:

- Moment arm length
- Normalized fiber lengths
- Regional muscle size
- Tendon stiffness
- Muscle stiffness
- Neural drive

The angle of peak torque can change even after normal strength training, probably because of changes in many of these factors, including neural drive, normalized fiber length, regional muscle size, tendon stiffness, and muscle stiffness.

Depending on how much each of these factors alters, the angle of peak torque can either move to a joint angle that corresponds to a shorter muscle length, or to a joint angle that corresponds to a longer muscle length.

Factors that shift the angle of peak torque to longer muscle lengths after normal strength training include increases in neural drive at long muscle lengths, increases in normalized fiber length, specific gains in regional muscle size, and increases in muscle stiffness. Factors that shift the angle of peak torque to shorter muscle lengths after normal strength training include increases in neural drive at short muscle lengths, decreases in normalized fiber length, specific gains in regional muscle size, and increases in tendon stiffness.
Long vs. short muscle length isometric training


Interestingly, these joint angle-specific gains in strength are smaller when the muscle is trained isometrically at long muscle lengths, compared to when it is trained isometrically at short lengths (Bandy & Hanten, 1993; Kubo et al. 2006; Ullrich et al. 2009; Noorkõiv et al. 2014), but there is still some specificity. Also, shifts in the angle of peak torque towards the trained joint angle can occur after isometric training at long muscle lengths (Ullrich et al. 2009; Alegre et al. 2014).

Bandy & Hanten (1993) tested isometric strength at multiple joint angles in three groups who performed isometric knee extension training at either short muscle lengths (30 degrees of knee flexion), moderate muscle lengths (60 degrees of knee flexion) or long muscle lengths (90 degrees of knee flexion), where full knee extension is 0 degrees of knee flexion. The results are shown in the chart below.

You can see the differences between the groups in joint angle-specific strength gains immediately.
The blue line shows the effect of training at short muscle lengths (30 degrees), and the increase in strength is only around the trained joint angle. The orange line shows the effect of training at moderate muscle lengths (60 degrees), and the increase in strength has a peak at the trained joint angle, but there is also a response at other joint angles. The green line shows the effect of training at long muscle lengths (90 degrees), and the increase in strength is strongest at the trained joint angle, but there is also a smaller response at shorter muscle lengths.

Since these results are not unusual, there is clearly a different type of joint angle-specific strength gain after isometric training with short muscle lengths, compared to after isometric training with long muscle lengths.

Why is this?

Traditionally, it has been assumed that neural factors were responsible for joint angle-specific gains in strength after isometric training at all joint angles (Kitai & Sale, 1989; Noorkõiv et al. 2014). However, as you can see from the chart below showing the gains in EMG amplitude reported by Bandy & Hanten (1993), the changes are similar in each training group, and increases in joint angle-specific neural drive cannot explain the difference in the shape of the curves for the gains in strength.
Recent research has found that changes in joint angle-specific neural drive are indeed responsible for the joint angle-specific gains in strength after isometric training at short muscle lengths (Alegre et al. 2014; Noorkõiv et al. 2014).

On the other hand, regional hypertrophy seems to be more important than changes in joint angle-specific neural drive for the joint angle-specific gains in strength after isometric training at long muscle lengths (Alegre et al. 2014; Noorkõiv et al. 2014).

This explains why joint angle-specific strength gains differ between isometric training with either long or short muscle lengths.

They are caused by different adaptations.

Neural drive is mainly responsible for joint angle-specific gains in strength at short muscle lengths, while regional hypertrophy is more important for joint angle-specific gains in strength at long muscle lengths.
Partial vs. full range of motion exercises (part 1)

Now, here is the thing. Biomechanically, isometric training with short muscle lengths is quite similar to partial range of motion training with constant-load, free weight exercises, like the barbell back squat. And isometric training at long muscle lengths is similar to full range of motion training with constant-load, free weight exercises. There are two reasons for this.

Firstly, when you exert force against the barbell, total vertical force differs across the phases of the lift. This is because total force comprises weight (force to counteract gravity) and inertia (force to accelerate mass). Each part of the lift requires different amounts of acceleration, and different amounts of force. The start of the lifting phase needs most acceleration, and the greatest amount of force. Total vertical force is 10 – 20% bigger at the start of the lifting phase compared to the rest of the lift.

Secondly, external moment arms at the hip and knee are long at the start of a lift like the back squat, and they get smaller as you lift the weight. This means that even though the weight of the barbell does not change, the hip and knee joint torques produced by the barbell are greatest at the start of the lift, and reduce as you rise upwards.
In other words, whether the exercise is a partial movement or a full range of motion movement, if you are using a constant-load, free weight exercise such as the barbell back squat, your muscles have to contract really, really hard at the start of the lift. After that the exercise gets much easier very quickly.

If you are doing a partial squat, then you will carry out this peak contraction at a fairly short muscle length. On the other hand, if you are doing a full squat, then you will carry out this peak contraction at much longer muscle lengths.

So full and partial range of motion training are not so very different from long and short isometric training, really.

**Partial vs. full range of motion exercises (part 2)**

If partial range of motion training with free weights is similar to isometric training at short muscle lengths, then we should see parallels between the two types of training. Similarly, if full range of motion training with free weights is similar to isometric training with long muscle lengths, then we should see parallels between those two types of training as well.

We should see joint angle-specific gains in strength after partial range of motion training being caused by increases in joint angle-specific neural drive, and we should see joint angle-specific gains in strength after full range of motion training being caused by regional hypertrophy.

Indeed, full range of motion training does produce greater changes in either muscle thickness (Pinto et al. 2012; McMahon et al. 2013), muscle cross-sectional area (McMahon et al. 2014) or regional muscle cross-sectional area (Bloomquist et al. 2013) in comparison with partial range of motion training.

There is less information regarding the changes in EMG amplitude after partial range of motion training. Even so, McMahon et al. (2013) did find that full range of motion training produced similar increases in EMG amplitude at all joint angles, while partial range of motion training left EMG amplitude unchanged at short muscle lengths, and reduced EMG amplitude at longer muscle lengths. While the overall size of the change is unexpected, this does follow the right shape of curve, with the change at short muscle lengths being larger than the change at longer muscle lengths.
Conclusions

Partial squats make you stronger at doing partial squats, but do not transfer well to full squats. This is probably also applicable for some other exercises, particularly those where external moment arm lengths change substantially in the lifting phase. In contrast, full squats make you stronger at full squats, and also transfer somewhat to partial squats (but not as well as partial squats).

Similarly, isometric training at short muscle lengths improves strength at that joint range of motion, and only improves strength very slightly (if at all) at longer muscle lengths. Isometric training at long muscle lengths improves strength at that joint range of motion, and also (albeit slightly less) at shorter muscle lengths.

Partial and full range of motion training are not as different as you might think from isometric training at short and long muscle lengths. Many exercises with free weights are like squats and have external moment arms that are long at the bottom of the movement, and short at the top. So the total range of motion of the exercise (partial or full) determines the muscle length at which the peak contraction occurs.

It seems likely that these kinds of partial exercises improve strength at short muscle lengths mainly because of joint-angle specific increases in neural drive, while comparable full range of motion exercises may improve strength at long muscle lengths, mainly because of differences in regional hypertrophy.
References


5. EXTERNAL LOAD TYPE
Conventional weight training involving multi-joint exercises, often using barbells, is the most commonly-used and well-researched strength training method for improving athletic ability.

Of course, there are other methods available. Some of these are completely different from conventional weight training (such as many types of modern machines), while others differ by starting with barbells and then adding elastic bands or chains to produce a different stimulus.

When debating the advantages and disadvantages of different strength training methods for athletes, most reviewers focus on whether the stability demands of the method are similar to those required in sport. Few reviewers have considered how using only weight can produce a different training effect compared with other types of strength training, because of where in the exercise range of motion each method produces a peak muscle contraction. And this is a very unappreciated, but extremely important factor.

Where this peak muscle contraction occurs is determined by the external load type.

**What is external load type?**

External load type refers to the material that is used to produce resistance to movement. In this way, it indirectly describes how the externally-applied force changes throughout the range of motion of the exercise.

External load types include pneumatic resistance, elastic resistance, weights (including free weights, chains, and machines), and dynamometers (which use magnets). All of these can be used to produce slightly different levels of externally-applied force at different points in the exercise range of motion.

For example, a barbell squat or bench press can be performed with just free weights, with free weights plus elastic bands, with free weights plus chains, with just chains on an empty barbell, or with just bands on an empty barbell.

The barbell squat or bench press with free weights has an externally-applied force that is mostly (but not entirely) constant over the exercise range of motion, while the barbell squat or bench press with just bands on an empty barbell is at the other extreme. The externally-applied force varies from nearly zero at the bottom of the exercise, to very large at the top.
How does external load type alter the externally-applied force?

In theory, the externally-applied force can either vary across the whole joint angle range of motion, or it can remain constant. In practice, it is quite rare for an externally-applied force to remain completely constant during an exercise.

The way in which the externally-applied force changes over the exercise range of motion is not determined by a single factor. Many different forces can act in the overall range of motion during strength training, depending on the set-up. These include:

- Weight due to gravity
- Inertia due to mass
- Rotational inertia due to rotating mass in a flywheel
- Tension produced by lengthened elastic bands
- Electromagnetic force in a dynamometer
- Air resistance in a pneumatic device

Some of these types of external resistance change depending on other external factors, while others do not.

For example, weight does not change, irrespective of where it is in the exercise range of motion, nor does it change in response to how much it is accelerated. In contrast, the tension produced by elastic bands is highly dependent upon where you test it in the exercise range of motion, as it is nearly zero when the bands are slack but very high when they are taut. Similarly, inertia and rotational inertia are highly dependent upon the amount of acceleration that the load is subjected to. They are zero when acceleration is zero but are very high when acceleration is high.
Why is a free weight not a constant externally-applied force?

Although the weight or load remains constant throughout a free weight exercise, the externally-applied force is not constant, because the total externally-applied force is not solely caused by weight, but is equal to weight plus inertia.

The force due to inertia is dependent upon how fast the barbell is being accelerated. Acceleration is always high at the start of the movement and zero when the barbell reaches peak velocity.

For example, in the barbell back squat using free weights, the externally-applied force in the middle of the exercise is largely just due to the weight of the barbell, while the force at the start of the concentric is around 10 – 20% higher. At this point, the externally-applied force is made up of both the weight of the barbell and the inertia in accelerating the barbell up to its maximum speed.

When using free weights during multi-joint exercises, the externally-applied force is almost always greatest at the beginning of the concentric phase, and this is where muscle lengths are longest.
What do externally-applied forces look like?

Externally-applied force differs depending on the type of external load. We can see this in action if we sketch the torque-angle curves of a single-joint exercise when performed with a couple of different external load types, like this:

As you can see, even though the exercise is the same, the externally-applied torque, or turning force, differs with joint angle between the external load types.

The isokinetic load type makes the muscle work as hard as it possibly can at every individual point in the movement, so it rises to a peak at the angle of peak torque, which is usually somewhere in the middle of the joint range of motion (but remember that angle of peak torque varies with velocity).

An isotonic external load type can display a slightly different profile at the beginning and end of the curve depending on the exact set-up used, but typically has a very short period where the load is low before whatever machine is being used "kicks in" and starts resisting the movement with a fixed torque.
The constant load (which as noted above is not a constant externally-applied force) always displays a much higher torque at the start of the contraction, which is where the muscle length is longest, because the start of the contraction involves working against both gravity and inertia, while the middle of the contraction involves only working against gravity, and the end of the contraction involves riding along with momentum as the weight comes to a halt.

Although this example was for a single-joint exercise, the same effects also occur in multi-joint exercises.

Why do strength coaches use bands and chains?

Elastic bands or chains can be added to the barbell during multi-joint exercises like squats or bench presses.

In many common multi-joint exercises, like the squat and bench press, external moment arm lengths decrease with increasing bar height. This means that the exercise naturally becomes easier as the lifter progresses through the range of motion.

By adding bands and chains, the externally-applied force is increased, and this counteracts the impact of the reducing external moment arm lengths.

This leads to a more constant level of muscle force throughout the movement. This is often called accommodating resistance.
How does using bands and chains affect strength gains?

Training with bands and chains seems to produce slightly greater gains in strength in advanced but not in novice trainees (Soria-Gila et al. 2015), although exactly why this happens is unclear. There are many possible explanations.

Some authors have suggested that training with bands and chains targets the "sticking region" of a lift, although why this should be the case for advanced lifters and not novices is unclear.

Others propose that it might be because training with bands and chains produces greater hypertrophy, although to date this has not been assessed. But similar investigations using multi-joint machine exercises with either constant or variable load resistance have found no differences in hypertrophy (Walker et al. 2013).

Another possibility is that accommodating resistance leads to a greater bar speed, and a more consistent intent to accelerate the barbell, both of which produce specific adaptations that are helpful for increasing high-velocity strength, and high-velocity strength transfers better to low-velocity strength than the other way around.

Alternatively, it may be the case that accommodating resistance is usually a novel stimulus to most trainees (even experienced ones) and this might explain the superior effects in advanced trainees that are not mirrored in beginners.

Whatever the explanation, there is one downside.

Adding bands and chains is usually done in combination with reducing the amount of weight plates on the barbell. So the increase in force later on in the exercise range of motion (where muscle lengths are short) happens at the expense of reducing the peak muscle force at the start of the concentric phase of the exercise (where muscle lengths are long). And this might well produce joint angle-specific gains in strength, because of the focus at different muscle lengths.

Let's take a look.
How do different externally-applied forces affect strength gains with different types of external load?

Many studies have compared the effects of different types of externally-applied forces on external load type-specific strength gains. In general, these studies tend to compare constant and variable loads, and largely fall into three main categories:

**Powerlifting** – those that have explored the use of bands or chains in combination with barbell free weights (variable resistance) compared with free weights only (constant loads) during the bench press or back squat;

**Machines** – those that have compared variable weights and constant weights using machines for improving strength; and

**Rehabilitation** – those that have compared elastic resistance (variable resistance) and free weights (constant loads) during rehabilitation exercises.

*The powerlifting studies*

When looking at studies exploring the effects of adding bands or chains on specific strength gains in the powerlifting exercises, most studies have reported that it does not matter whether subjects use free weights alone, or free weights with added bands or chains.

Free weights only and free weights plus either bands or chains seem to produce similar gains in 1RM free weight squat or bench press (Anderson et al. 2008; McCurdy et al. 2009; Ghigiarelli et al. 2009; Rhea et al. 2009; Shoeppe et al. 2011; Joy et al. 2014; Jones, 2014; Ataee et al. 2014; Calatayud et al. 2015; Andersen et al. 2015).

There is only a small amount of evidence that specificity does occur.

And yet, that specificity is related to muscle length, as expected. Andersen et al. (2015) reported joint angle-specific gains in strength, whereby squats with free weights produced gains in isometric strength at both 60 and 90 degrees of knee flexion, while squats against elastic bands produced gains in isometric strength only at 60 degrees of knee flexion.
The machine studies

When looking at studies reporting on the external load type specificity of strength gains after long-term training programs performed on machines with both eccentric and concentric muscle actions, there are conflicting reports.

Some studies have reported no external load type specificity of strength gains, although these are primarily limited to those reporting on programs of single-joint knee extension exercises (Manning et al. 1990; Hunter & Culpepper, 1995; Remaud et al. 2010) or programs of combined single-joint and multi-joint leg extension exercises (Walker et al. 2013). Where these studies assessed joint angle-specific changes in strength, they found no effects (Manning et al. 1990; Remaud et al. 2010).

Many similar studies have found that strength gains are specific to the type of external load used. These studies have reported on programs of single-joint knee extension exercise (Smith & Melton, 1981; Kovaleski et al. 1995; Wojtys et al. 1996; Golik-Peric et al. 2011), and on programs of single-joint elbow flexion exercise (O’Hagan et al. 1995; Staniszewski et al. 2016). Some studies have even tested the effects of different types of external load during programs involving a range of upper and lower body single-joint and multi-joint exercises (Pipes & Wilmore, 1974; Pipes, 1978; Frost et al. 2015), and these produced quite a bit of specificity, as shown below.

![Diagram showing changes in constant or variable strength after training using either constant or variable resistance](Image)

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The rehabilitation studies

When comparing rehabilitation exercises performed with solely elastic resistance or with solely free weights, most studies have generally reported no external load specific strength gains (Behm, 1991; Colado et al. 2010).

In summary, we only observe external load-type specific strength gains in some groups of study and not in others, which suggests that the specificity of external load type is probably quite weak.

So what is causing these weak effects (and why are they small)?

What might cause the weak specificity in strength gains for external load type?

Previously, I explained how partial range of motion exercises produce joint angle-specific gains in strength for the same reasons as isometric training at short muscle lengths, which is mainly through neural adaptations. In contrast, full range of motion exercises produce similar patterns of strength gains to isometric training at long muscle lengths, mainly through regional hypertrophy.

External load types probably produce specificity for the same reasons.

Free weights and other constant loads (even those involving machines) during most common exercises produce a peak contraction at long muscle lengths (there are some exceptions). Most other types of external load, including those that add bands and chains to barbells, reduce the size of the peak contraction at long muscle lengths and increase it at shorter muscle lengths.

If this is the case, we should find that the main causes of specificity in strength gains after training with different types of external load are regional hypertrophy and joint angle-specific changes in neural drive (especially at end range of motion).

So is there any evidence for this?
Does regional hypertrophy cause specificity of strength gains with different types of external load?

Few studies have reported on changes in regional hypertrophy when comparing groups training with different types of external load.

In one study comparing the effects of training with a machine knee extension and with an isokinetic dynamometer, Matta et al. (2015a) reported that hypertrophy in individual quadriceps muscles differed between the two types of training. Although both types of external load were variable, the machine knee extension would still have involved a larger contraction at longer muscle lengths than the isokinetic device.

The results are shown in the chart below.

![Chart showing changes in individual quadriceps muscle thickness after training using either machine or dynamometer knee extensions.](chart.png)

Similarly, and using exactly the same training programs and exercise comparisons, Matta et al. (2015b) found that the same phenomenon occurred in respect of the individual parts of the rectus femoris.

So regional hypertrophy occurs both within muscle groups and within parts of the same muscle, after training with different types of external load.
Do joint angle-specific changes in neural drive cause specificity of strength gains with different types of external load?

Few studies have reported on changes in neural drive at different joint angles when comparing groups training with different types of external load.

In one study, Remaud et al. (2010) assessed joint angle-specific changes in maximum voluntary isometric contraction (MVIC) torque and in neural drive after isotonic and isokinetic types of external load, using knee extension training. They tested joint angles from long (90 degrees of knee flexion) to short (30 degrees of knee flexion) muscle lengths, expecting to see greater gains for the isotonic group at both ends of the range of motion, where loading was higher than in the middle.

In fact, they found no significant differences between groups. Even so, we need not despair, as they did observe a non-significant trend towards greater torque at short muscle lengths in the isotonic group, as well as a non-significant trend towards greater EMG amplitude at both ends, as you can see in the pair of charts below.
It is interesting that the non-significant EMG amplitude changes after isotonic training follow a U-shaped curve, but only contribute to greater torque increases than the middle range of motion at short muscle lengths (30 degrees). This is in line with the expected effects of joint angle-specific changes in neural drive being most relevant at short muscle lengths.

Fortunately, other research supports the presence of external load specificity in conjunction with joint angle-specific differences in neural drive.

Using eccentric-only knee extension training, Guilhem et al. (2013) assessed the effect of constant load and isokinetic external load types on joint-angle specific changes in torque and EMG amplitude.

They found that constant load training led to increases in both torque and EMG amplitude at all muscle lengths. In contrast, isokinetic training failed to improve torque at short muscle lengths (35 and 45 degrees), and also failed to increase EMG amplitude at long muscle lengths (85 degrees).
Why is the specificity in strength gains for external load type so weak?

Why is the specificity weak?

Isometric training at long muscle lengths is very different from isometric training at short muscle lengths. At no point does it ever involve loading while the muscle is short. Consequently, each displays remarkable joint angle-specific strength gains.

Full range of motion training is only moderately different from partial range of motion training, as there are some points where contractions occur at the same muscle lengths. The key differences are that the partial range of motion training involves no crossover with the full range of motion training, and also involves a heavier load in the upper part of the exercise range of motion. And joint angle-specific strength gains are smaller than after isometric training at short vs. long muscle lengths.

Free weight training is only slightly different from variable or accommodating resistance training, as contractions always occur at the same muscle lengths. The only difference is that the accommodating resistance involves a lighter load in the lower part of the exercise range of motion, and a heavier load in the upper part of the exercise range of motion. And joint angle-specific strength gains are smaller than after partial range of motion training vs. full range of motion training.

So we can see the following hierarchy of reducing specificity:

• Long vs. short isometrics

• Full range of motion vs. partial range of motion

• Conventional free weight training vs. accommodating resistance training
**What does this mean in practice?**

What type of training is best depends both on your goals, and also on your capacity for improvement.

If your main goal is to improve strength towards the end of the concentric phase of an exercise range of motion (e.g. you compete in equipped powerlifting, where suits provide help at the start of the concentric phase), then isometrics at short muscle lengths, partials or accommodating resistance could all work very well.

Deciding which is better depends on where you have room for improvement. Isometrics at short muscle lengths or heavy partials will give you better strength gains around the specific joint range of motion compared to accommodating resistance, but accommodating resistance has the added benefit of producing more hypertrophy than partials. So if you are already up against your limit for gaining muscle, then isometrics at short muscle lengths or partials may be best. If you are still making size gains, then accommodating resistance is probably a better bet.

On the other hand, if your main goal is to improve athletic performance, or if you are a powerlifter who competes without equipment, then your primary goal should be to develop the ability to produce force at long muscle lengths, because partial exercises do not transfer to sport. In this case, you are best off sticking to constant-load, full range of motion exercises, and only using accommodating resistance if you need the variety.
Conclusions

Conventional weight training (using either barbells or constant-load machines) produce a peak muscle contraction at the start of the concentric phase, where muscle lengths are longest.

In contrast, variable loads (using either barbells plus bands or chains, or variable-load machines) produce even muscle forces over the exercise range of motion. These differences in externally-applied force over an exercise range of motion lead to joint angle-specific strength gains.

These joint angle-specific strength gains are similar to the effects produced by full vs. partial range of motion training, or isometrics at long vs. short muscle lengths, and are probably caused by differences in regional hypertrophy and joint angle-specific changes in neural drive (especially at end range of motion).

Whether constant-load or variable-load training is best for you depends both on your goals, and also on your capacity for improvement. However, since athletes are likely to benefit to a greater extent from the specific strength gains that come with training at longer muscle lengths, conventional weight training is often going to be best for improving sports performance.
References


6. EXTERNAL LOAD STABILITY
Many strength coaches recommend against training on unstable surfaces when using free weights for improving sports performance. Leaving aside potential safety issues, the main reason given is that lighter weights are used in less stable conditions. And using lighter weights is thought to cause smaller strength gains.

Many coaches also recommend against using multi-joint machines, like the leg press, when preparing athletes for sport. In this case, the main underlying reason is that the strength gains will not transfer to a less stable environment (they are not functional), where some degree of balance is required.

So do free weights involve a level of external load stability that is just right when preparing athletes for sport? Or is all of this just wishful thinking?

**What is external load stability?**

The stability of the external load determines how much balance is needed when doing an exercise. External load stability exists on a continuum from very stable, to neutrally stable, to very unstable. Less stability means more balance is needed, while more stability means that less balance is required.

Changes in stability involve altering the type of resistance used, or the type of surface on which the lifter is standing, sitting, or lying. A bench press can be performed in a highly stable set-up (on a bench with a barbell), in a moderately stable set-up (on a bench with dumbbells), or in a very unstable set-up (on a Swiss ball with dumbbells).
Changing from a barbell to dumbbells involves altering the stability of the external resistance directly, while changing from a bench to a Swiss ball involves altering the stability of the surface upon which the lifter is resting. Both of these changes alter the stability requirements, and therefore the need to balance, but in different ways.

**Why is external load stability important?**

If strength gains are stability-specific, then gains in strength in a very stable exercise set-up (such as sitting on a machine) might not transfer to strength displayed in less stable environments (such as standing on the ground), while gains in very unstable environments (such as balancing on a wobble board) might not transfer to those in more stable environments (Willardson, 2004).

This is important for athletes, who tend to spend much of their time exerting force into the ground.

There are clues that strength is indeed stability-specific.

For example, the association between a machine 1RM and a similar exercise free weights 1RM can range between moderate and strong (Willardson & Bressel, 2004; Cotterman et al. 2005; Langford et al. 2007; Lyons et al. 2010; Mayhew et al. 2010; Ferraresi et al. 2013). This suggests that there are some factors that differ as a result of the stability requirement. Otherwise, the relationship would be very strong, as everyone would simply scale their strength levels between stable and unstable exercises in the same way.

If this is the case, then we should probably be trying to match the stability requirements of the exercise to the stability requirements of the sport.
Comparing training with machines and free weights

The advantages and disadvantages of training with either machines or free weights have been debated at great length (e.g. Stone et al. 2000; Haff, 2000). Here, I want to focus on whether strength gains are stability-specific. To do this, we can look at studies comparing the following:

1. Training with machines vs. free weights, then testing free weights strength.
2. Training with machines vs. free weights, then testing an athletic ability.

#1. Comparisons of machine and free weights training on free weights strength

More studies than you might expect have assessed the effects of long-term training programs with machines on strength tested with free weights in young adults (Boyer, 1990; Augustsson et al. 1998; Langford et al. 2007; Lennon et al. 2010; Mayhew et al. 2010; Ratamess et al. 2016). Without exception, every single study has shown that training using machines can improve strength as measured using free weights.

Several of these studies have also compared the effects of training with machines with the effects of training with free weights on strength tested with free weights (Boyer, 1990; Augustsson et al. 1998; Langford et al. 2007; Mayhew et al. 2010; Lennon et al. 2010).

Only Langford et al. (2007) found no evidence of stability-specificity when training with machines or free weights, possibly because the difference in stability between conditions may not have been that substantial, as indicated by the small difference in force between exercise variations of just 3 – 8%. Most have found evidence of stability-specificity in both directions, both when the exercises performed are very similar (Boyer, 1990; Lennon et al. 2010; Mayhew et al. 2010), and when they are different (Augustsson et al. 1998).
#2. Comparisons of machine and free weights training on athletic performance

Many studies have assessed the effects of training the lower body with machines on sports performance in young, healthy adults.

Improving leg press strength seems to transfer reasonably well to greater vertical jump height (Silvester & Bryce, 1981; Papadopoulos et al. 2014; Wirth et al. 2015; Manolopoulos et al. 2016) as well as single-leg hop for distance (Wawrzyniak et al. 1996). Smith machine squat training seems to improve vertical jump height and sprint running ability (De Hoyo et al. 2015b). Even the knee extension can improve vertical jump height (Augustsson et al. 1998; Friedmann-Bette et al. 2010).

Flywheel training is an increasingly popular form of machine training, although arguably this requires more control than a more traditional machine with a fixed bar path, since it uses a cable to direct the force. Flywheel squat training seems to transfer very well to vertical jump height (Sheppard et al. 2008; Gual et al. 2015; De Hoyo et al. 2015a), and flywheel leg curl training transfers well to sprint running (Askling et al. 2003; De Hoyo et al. 2015a).

So training using machines does transfer to sporting performance, despite what some alarmists might tell you.

Unfortunately, far fewer studies have compared the effects of machine and free weights training in young adults on athletic performance (Augustsson et al. 1998; Wirth et al. 2015). Even so, both of these studies confirm that machine training does not transfer as well to vertical jumping ability as free weights, both when the exercises used are similar (Wirth et al. 2015), and when they are different (Augustsson et al. 1998).

To summarize, machine training does improve free weights strength, but not by as much as free weight training (and the other way around). Stability-specific strength gains do happen. And also, machine weight training can improve athletic ability, but not by as much as free weight training.
Comparing training with stable or unstable machines

In some training studies, different types of machines have been compared with one another, where one type of machine makes use of fixed bar paths and the other type of machine uses cables that allow freedom of movement, to perform essentially the same multi-joint exercise (Spennewyn, 2008; Cacchio et al. 2008).

Strength gains are different between the two types of machine, and there is again definite evidence of stability-specific gains in strength going in both directions (Cacchio et al. 2008).

Interestingly, these studies also show that gains in dynamic strength, when tested in the machine on which the training was performed, are much higher when training with the cable machines than when training with fixed bar path machines (Spennewyn, 2008; Cacchio et al. 2008).

This suggests that there may well be a learning component inherent in using the cable machines that contributes substantially to the gains in strength. Indeed, Cacchio et al. (2008) did note that training with the cable machines led to beneficial alterations in the EMG amplitudes of the stabilizers and of the antagonist muscles, while training with the fixed bar path machines did not.

We will come back to this point later on.
Comparing training on stable and unstable surfaces

The advantages and disadvantages of unstable surface training have also been discussed ad nauseam (e.g. Hubbard, 2010; Behm & Sanchez, 2013). Here, I want to focus on whether strength gains are stability-specific. To do this, we can look at studies exploring:

1. Training with stable vs. unstable surfaces, then testing strength on stable surfaces.
2. Training with stable vs. unstable surfaces, then testing an athletic ability.

#1. Comparisons of training on stable vs. unstable surfaces on strength on stable surfaces

Very few studies have compared the effects of training on stable vs. unstable surfaces on strength on stable surfaces. Those that have are summarized in a recent systematic review (Behm et al. 2015), although the measures used to assess strength are not differentiated, which makes the results difficult to interpret.

The most stable surface typically measured in studies is maximum isometric force, using a dynamometer. Training on unstable surfaces tends to produce similar gains in maximum isometric force as training on stable surfaces (Kibele & Behm, 2009; Sparkes & Behm, 2010; Prieske et al. 2016).

The second most stable surface typically measured in studies is maximum dynamic force, using the strength exercise used in the stable-surface training group, such as 1RM bench press (Cowley et al. 2007; Marinković et al. 2012; Premkumar et al. 2012; Maté-Muñoz et al. 2014), 3RM bench press (Sparkes & Behm, 2010), 1RM back squat (Marinković et al. 2012; Maté-Muñoz et al. 2014), and 3RM back squat (Sparkes & Behm, 2010).

Training on unstable surfaces seems to produce similar gains in dynamic strength in the exercise used during training, compared to training with the same exercise on stable surfaces.
This suggests that there is no evidence of stability-specific strength when testing strength on stable surfaces after either stable or unstable surface training. However, although not as well-researched, there are some suggestions that gains in strength on unstable surfaces might be greater after training on unstable surfaces (Sparkes & Behm, 2010), which would mean that stability-specific strength gains still occur, albeit only in one direction.

Importantly, however, all of these studies were performed in untrained individuals.

Since there are indications that unstable surface training does not lead to greater EMG amplitudes than stable surface training with the same absolute loads in resistance-trained individuals (Wahl & Behm, 2008; Li et al. 2013), training on unstable surfaces may not be as effective as training on stable surfaces in trained subjects.

#2. Comparisons of training on stable vs. unstable surfaces on athletic performance

Very few studies have compared the effects of training on stable vs. unstable surfaces on athletic performance measures. Those that have are summarized in a recent systematic review (Behm et al. 2015), although the measures used to assess athletic ability are not differentiated, which makes the results difficult to interpret.

Looking only at those studies exploring the effects of lower body strength training on countermovement jump height, a majority have found that performing the exercises on stable surfaces is better than performing the exercises on unstable surfaces (Cressey et al. 2007; Oberacker et al. 2012), although a minority have found no differences (Maté-Muñoz et al. 2014).

This suggests that lower body training on unstable surfaces may not transfer as well to the same exercises performed on the ground for common tests of athletic ability, such as vertical jumping.

To summarize, unstable surface training does improve strength on stable surfaces to a similar extent as stable surface training in untrained subjects. However, this may not apply to trained individuals. And also, unstable surface training may not improve common tests of athletic ability as well as the same exercises performed on the ground.
What mechanisms cause stability-specific strength gains?

Given that stability-specific strength gains do occur, what might be the underlying mechanisms?

One difference between more stable and less stable exercises is the amount of force that is produced. This could be a mechanism by which stability-specific strength gains occur, if the greater force exerted in the more stable conditions then leads to greater neuromuscular adaptations.

Another difference between more stable and less stable exercises is the amount of balance that is needed. Differences in the need to balance could produce adaptations involving mechanisms by which stability-specific strength gains then occur. Balance requirements could produce improvements in strength simply by being a balance challenge (as balance training does have neural effects), or because they alter the way in which an exercise is performed, thereby changing the co-ordination and muscles involved in the movement.

Let's take a look at both of these possibilities, and see which of them might be responsible for stability-specific strength gains.
Does force production lead to stability-specific strength gains (part 1)?

When using machines to perform an exercise with the same relative load, the force involved is usually (but not always) greater than when using free weights to perform a very similar exercise (Cotterman et al. 2005; Cowley et al. 2007; Lyons et al. 2010). Similarly, when using unstable surfaces to perform an exercise with the same relative load, the force involved is usually (but not always) less than when using the same exercise on a stable surface (Goodman et al. 2008; Behm & Colado, 2012).

The size of the difference caused by stability changes depends on the exercise (Cotterman et al. 2005), on the muscle group (Lehman et al. 2006), and of course on how much instability is involved.

Even so, it is largely true that more stability = more force; less stability = less force.

Does force production lead to stability-specific strength gains (part 2)?

For the greater externally-applied force during more stable exercises to produce greater neuromuscular adaptations, it needs to translate to greater internal muscle force.

Muscle activation, as measured by EMG amplitude, is a good proxy for internal muscle force production, particularly when measurements are taken under non-fatiguing conditions, and when the muscle action is isometric.

When investigating exercises performed with the same relative load (which means a lower absolute load in the unstable condition), some researchers have found that EMG amplitude of the prime movers is similar in exercises performed in unstable and stable environments. This has been found both during isometric (Anderson & Behm, 2004; Saeterbakken & Fimland, 2013a) and dynamic (Anderson & Behm, 2004; Welsch et al. 2005; Goodman et al. 2008; Schick et al. 2010; Saeterbakken et al. 2011; Andersen et al. 2014) muscle actions.

Some have even reported that the EMG amplitude of the prime movers is higher when using an unstable environment, compared to a stable environment (McCaw & Friday, 1994; Schwanbeck et al. 2009; Saeterbakken & Fimland, 2013b; Fletcher & Bagley, 2014; Campbell et al. 2014).
On the other hand, many other researchers have reported that the EMG amplitudes of the prime movers are lower under unstable conditions than under stable conditions, both during isometric (McBride et al. 2006; Chulvi-Medrano et al. 2010) and dynamic (Kohler et al. 2010; Chulvi-Medrano et al. 2010; Saeterbakken & Fimland, 2013c; Andersen et al. 2014) muscle actions.

Although the findings of these studies are conflicting, it seems fairly clear that the greater external force in more stable exercises does not always translate to greater internal muscle forces.

Why might this be?

**Does force production lead to stability-specific strength gains (part 3)?**

When lighter loads are used in unstable environments, internal muscle force production might be higher than expected because of increased antagonist co-activation, and synergist activation (Anderson & Behm, 2005; Sparkes & Behm, 2010).

Force produced by the prime mover muscles is greater, because they are working to co-contract with the antagonist and synergist muscles in order to hold the body and/or the weights in place, as well as move them through space.

Indeed, unstable surfaces do produce greater activation of the synergists and antagonists. For example, middle (but not anterior) deltoid activation tends to be greater during free weight bench presses compared to Smith machine bench presses (Schick et al. 2010). Similarly, latissimus dorsi, posterior deltoid, biceps brachii, upper trapezius, and lower trapezius EMG amplitudes tend to be greater during a pressing exercise performed when using a cable machine compared to when using a fixed bar path machine.

This suggests that the greater externally-applied forces observed when performing an exercise under stable conditions probably only lead to slightly greater internal muscle forces compared to training under less stable conditions, because the muscles have to work harder against the antagonists and stabilizers in less stable environments. This increases agonist muscle forces, even when external loads are lower.
On this basis, we might anticipate training in stable environments to increase strength by slightly more than training in unstable environments, but the difference may not be as substantial as we might initially expect.

Additionally, since unstable surface training probably does not lead to greater EMG amplitudes than stable surface training with the same absolute loads in resistance-trained individuals (Wahl & Behm, 2008; Li et al. 2013), training on unstable surfaces may not be as effective in trained subjects.

Either way, there is no obvious reason why levels of force production should be a mechanism by which stability-specific strength gains occur.
Does the need to balance cause stability-specific strength gains (part 1)?

When using machines to perform an exercise, the balance challenge involved is smaller than when using free weights to perform a very similar exercise. Similarly, when using unstable surfaces, the balance challenge is greater than when performing the same exercise on a stable surface.

More stability = less need to balance; less stability = more need to balance.

Does the need to balance cause stability-specific strength gains (part 2)?

Surprisingly, balance training on its own can increase strength.

This could mean that the balance aspect of unstable surface training could lead to strength gains irrespective of the loading used.

Studies show that balance training even without concomitant strength training leads to strength gains (Heitkamp et al. 2001; 2002; Bruhn et al. 2006; Myer et al. 2006; Beurskens et al. 2015; Cug et al. 2016). Such gains seem to be connected with increases in rate of force development (Gruber & Gollhofer, 2004; Bruhn et al. 2006; Gruber et al. 2007; Behrens et al. 2015), probably caused by increases in early phase neural drive, through faster motor unit firing rates (Gruber & Gollhofer, 2004).

What is behind these changes is unclear.

Increases in neural drive after strength training are probably caused by increases in corticospinal excitability (Beck et al. 2007; Griffin & Cafarelli, 2007; Kidgell et al. 2010), at least partly because of reductions in corticospinal inhibition (Latella et al. 2012; Weier et al. 2012; Christie & Kamen, 2014; Rio et al. 2015).

At first glance, it might seem that balance training produces completely different neural adaptations, as it leads to reductions in corticospinal excitability in balance tests (Taube et al. 2007; Beck et al. 2007; Schubert et al. 2008). However, these reductions in corticospinal excitability are very task-specific, just like improvements in balance (Kümmel et al. 2016). In fact, corticospinal excitability is still elevated after balance training in tests that have not been practiced, including strength tests.
This shared underlying mechanism would explain why additional gains in strength do not arise either when balance training is preceded by a period of strength training (Bruhn et al. 2006), nor when a program of balance training is performed together with a program of strength training (Manolopoulos et al. 2016). It may also help explain how strength training can improve balance in a range of populations (Heitkamp et al. 2001; Anderson & Behm, 2005; Orr et al. 2008; Manolopoulos et al. 2016), and also increases co-ordination (Carroll et al. 2001).

So the improvements in strength after balance training and after strength training occur through a common mechanism. This may partly account for the surprisingly larger-than-expected gains in strength after training on unstable surfaces in untrained subjects (but perhaps not in trained individuals), although it does not explain stability-specific gains in strength.

Does the need to balance cause stability-specific strength gains (part 3)?

The need to balance seems to affect the co-ordination patterns of muscles during multi-joint exercises. This affects the extent to which force can be produced during specific, dynamic movements.

Performing an exercise in an unstable environment produces greater activation of the synergist and antagonist muscles compared to the exact same exercise performed under more stable conditions, even where agonist activation is similar (Cacchio et al. 2008; Schick et al. 2010).

More importantly, training in the unstable environment reduces the antagonist activation, and increases the activation of the stabilizers.

These changes lead to a more efficient pattern of muscular contractions in that specific, dynamic movement under unstable conditions, which improves strength very substantially, in a stability-specific way.

For example, when comparing training with cable machines and with fixed bar path machines, Cacchio et al. (2008) found that training with the cable machines led to increases in the EMG amplitudes of the stabilizers, and reductions in the EMG amplitudes of the antagonist muscles during a cable machine strength test, while training with the fixed bar path machines did not.
Given that performance in balance tasks is very task-specific (Kümmel et al. 2016), and also that changes in neural drive after balance training are very task-specific (Beck et al. 2007; Schubert et al. 2008), it therefore seems very likely that such changes in inter-muscular co-ordination during specific dynamic movements are the underlying mechanism that causes stability-specific strength gains.

Since free weight exercises performed on the ground (like barbell squats) are most similar in terms of stability requirements to athletic ability tests (like vertical jumps), this also explains why free weights are indeed just right in terms of external load stability, and therefore transfer most effectively.
Conclusions

Training in more stable environments (i.e. machines rather than free weights, or barbells rather than dumbbells) involves greater externally-applied forces. These greater externally-applied forces are only partly reflected in greater internal muscle forces (and possibly even less in trained individuals), because of the greater antagonist and stabilizer activation in unstable environments.

This suggests that more stability is better for enhancing force production, when stability is not a factor. Even so, levels of force production are probably not a mechanism by which stability-specific strength gains occur.

Balance training and strength training produce strength gains at least partly through a common mechanism. This may account for the some of the larger-than-expected gains in strength after training on unstable surfaces in untrained individuals, although again it does not explain stability-specific gains in strength.

The need to balance in an unstable environment affects the co-ordination patterns of muscles during multi-joint exercises, increasing the activation of the synergist and antagonists. This affects the extent to which force can be produced. Training in the unstable environment reduces antagonist, and increases synergist activation. This leads to a more efficient pattern of muscular contractions, which improves strength in a stability-specific way, and transfers best to athletic ability.
References


7. IMPLICATIONS FOR SPORT
So why does the idea that strength is specific actually matter?

It matters because it shows us that the best way to improve strength for a sport is to analyze the requirements of that sport in terms of muscle action, speed, range of motion, external load type, and stability.

Matching these features in your strength training program with those that are important in your sport will give you better sport-specific strength gains than doing a “one-size-fits-all” training program.

Take a quick glance at these principles and you can see that this is already where the cutting edge of sports performance lies today.

Everywhere you look, there is a big focus on eccentric contractions, which are essential when athletes find themselves needing to stop suddenly after winding up a big sprint. And there is also a big focus on higher velocity training, as coaches move towards training faster, with lighter loads. Both of these trends are easily predictable based on the concept of strength specificity.

On the other hand, bands and chains don’t get a lot of mileage these days, because they do not reflect the same strength curves that athletes face on the field, especially when muscles are contracting at higher speeds.

Similarly, while free weights are making a comeback, it is rare to see stability balls anywhere except in rehabilitation. Athletes simply do not require strength under additional levels of instability beyond what they get from using free weights. Again, these trends are easily predictable based on the idea of strength specificity.

Strength is specific.