Reverse Engineering in Strength and Conditioning:

Applications to Agility Training

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Abstract

Typically, a coach may follow a process in which they first identify the key performance indicators of their sport, determine the physical attributes that map back to them, and then distribute the development of those capacities over the allocated timeframe. Furthermore, effective training plans are based on a theoretical or biological basis for how we move and adapt to exercise stimuli, coupled with an understanding of how these are best sequenced, such that one stimulus and subsequent adaptation can potentiate the next. Thus, reverse or backward engineering, when appropriately converged with the plans of those devised around nutrition, conditioning, technical, and tactical training for example likely gives athletes the best chance of attaining their performance goals. The aim of this paper is to describe the application of reverse engineering, exampling it within the context of developing an athlete who can demonstrate a high level of agility.

Introduction

Reverse engineering, sometimes referred to as back engineering, is a process in which products are deconstructed to extract design information from them, so that they may be recreated (22, 36). Engineers may employ this strategy because a particular part of a machine is now malfunctioning and the originating manufacturers have since gone out of business or may no longer offer the part. So, through deductive reasoning (i.e., *top-down logic* as opposed to inductive reasoning which requires *up-down logic*), the engineers will set about trying to understand how a particular system or part accomplishes a task with very little insight into exactly how it did so.

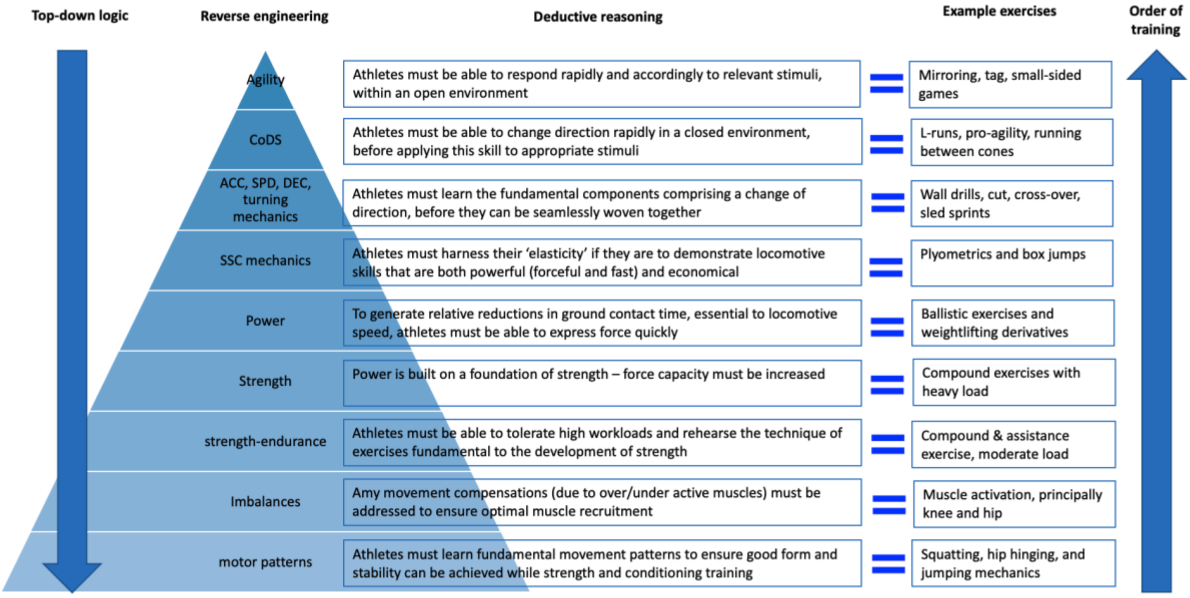
Reverse engineering is similarly adopted in systems biology (36) and likely extends to the field of strength and conditioning. In this regard, practitioners will design a series of training programs following a periodized and systematic approach, all of which stemmed from future-related competition or performance related goals (9, 16, 26, 30), whereby the coach considers the question *"where would we like to be this time next year"?* In this scenario, a coach may work backward, first identifying the key performance indicators of their sport, determine the physical attributes that map back to them, and then finally distribute the development of those capacities over the allocated timeframe (26, 32). Therefore, exercise selection, frequency, repetitions, sets, and rest, can be manipulated in such a way that ultimately maximizes sporting performance via the use of phase potentiation (9, 16, 23, 30).

It is expected that athletes who have successfully completed a deductively reasoned periodized training plan will increase their chance of performing at their best during the competitive period. That said, we should also acknowledge the obvious point that performance is multidimensional, requiring the convergence of technical, tactical, psychological, and social factors (13, 25). Thus, only being concerned with physical milestones (and strength-based ones at that) can be ineffective and overly reductionist. This framework should be seen as one layer of the performance puzzle, which needs to work in conjunction with the aforementioned factors, to give the athlete the best chance of meeting and ideally surpassing their competition based key performance indicators.

The aim of this article is to illustrate an evidence-based training plan, designed via the process of reverse engineering. We address how such an approach can help coaches to analyze the mechanisms underpinning physical preparedness, ultimately leading to the formulation of a high-performance road map. Our focus will be on physical training and the goal of our training program will be the development of an athlete who can demonstrate a high level of agility. That is, to be able to complete a direction change, responding rapidly and accordingly to relevant stimuli (39). Focusing on agility as our end goal should enable this process to be broadly applicable to many sports, athletes, and coaches.

Different paths to the same outcome

Before we start, we would note that the training suggestions and order presented herein, are based on our deductive reasoning; conceivably this top-down logic may differ across practitioners. Different paths to the same outcome are but one element that differentiates reverse engineering in biological systems to mechanical parts. Our focus, however, is on the process undertaken – that of reverse engineering – and the subsequent deductive reasoning based on an understanding of biological principles and phase potentiation. Furthermore, and accepting the prior note, we would also highlight that while the progression of training herein is often presented as linear (and in discrete blocks), it should not be interpreted as the athlete having to complete one block before moving on to the next. In contrast, each phase represents a temporal training emphasis, noting all modes can be trained concurrently. We just advise that the mode of training is emphasized in the order illustrated so that each phase is optimally potentiated. Our top-down reasoning is identified in Figure 1, with our thought process of how we arrived at this, detailed and evidenced in the following sections.



Reverse engineering	Deductive reasoning		Example exercises
Agility	Athletes must be able to respond rapidly and accordingly to relevant stimuli, within an open environment	=	Mirroring, tag, small-sided games
CoDS	Athletes must be able to change direction rapidly in a closed environment, before applying this skill to appropriate stimuli	=	L-runs, pro-agility, running between cones
ACC, SPD, DEC, turning mechanics	Athletes must learn the fundamental components comprising a change of direction, before they can be seamlessly woven together	=	Wall drills, cut, cross-over, sled sprints
SSC mechanics	Athletes must harness their 'elasticity' if they are to demonstrate locomotive skills that are both powerful (forceful and fast) and economical	=	Plyometrics and box jumps
Power	To generate relative reductions in ground contact time, essential to locomotive speed, athletes must be able to express force quickly	=	Ballistic exercises and weightlifting derivatives
Strength	Power is built on a foundation of strength – force capacity must be increased	=	Compound exercises with heavy load
strength-endurance	Athletes must be able to tolerate high workloads and rehearse the technique of exercises fundamental to the development of strength	=	Compound & assistance exercise, moderate load
Imbalances	Amy movement compensations (due to over/under active muscles) must be addressed to ensure optimal muscle recruitment	=	Muscle activation, principally knee and hip
motor patterns	Athletes must learn fundamental movement patterns to ensure good form and stability can be achieved while strength and conditioning training	=	Squatting, hip hinging, and jumping mechanics

Figure 1. The reverse engineering of agility. CoDS = change of direction speed, ACC = acceleration, SPD = speed, DEC = deceleration, SSC = stretch shortening cycle mechanics

Start with the end in mind: Agility and change of direction speed

Two fundamental components define agility: (a) decision making and (b) change of direction speed (CoDS) (39). Decision making is arguably best developed through sport practice and competition, so we will focus our attention on CoDS; however, we will include reactive drills such as partner tag and mirroring for example. CoDS centers on an athlete's physical capacity to accelerate, decelerate, and turn, as well as their capacity to seamlessly complete any given sequence of these rapidly (Figure 2) (29). Without the development of the relevant discrete motor skills, an efficient change of direction will not be possible, compromising agility and thus sports performance, and potentially even increasing injury risk (20). In summary, our end goal is to develop an athlete who is both technically proficient and fast relative to their teammates and opponents, across a range of CoDS tests, and thus we must map our journey back to this.

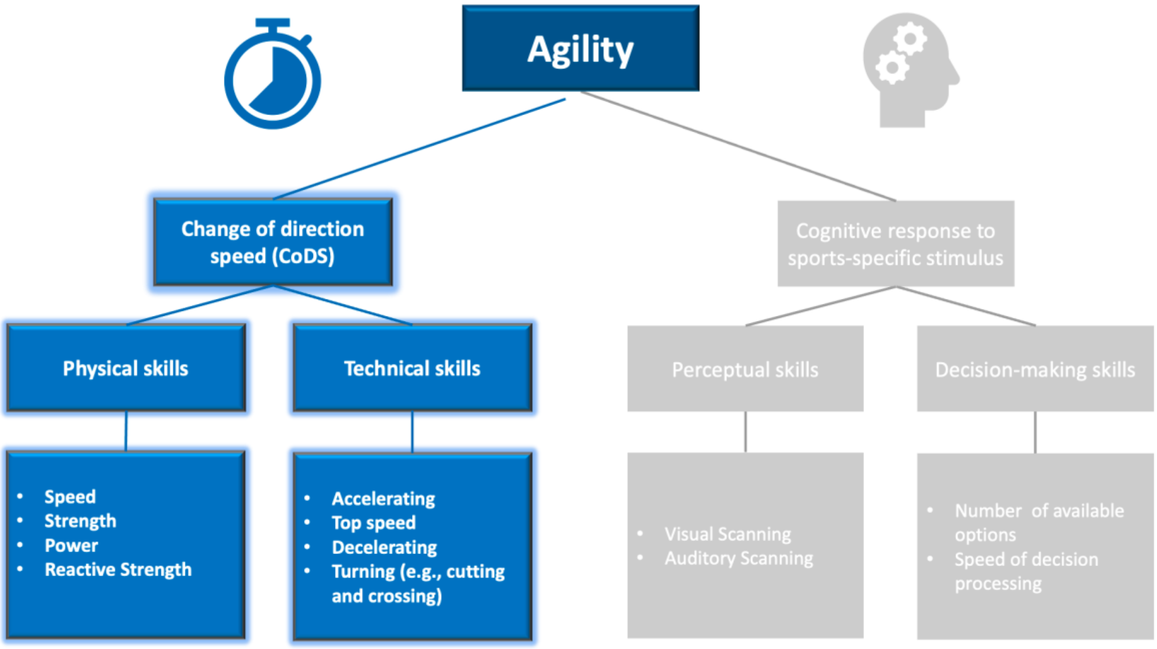
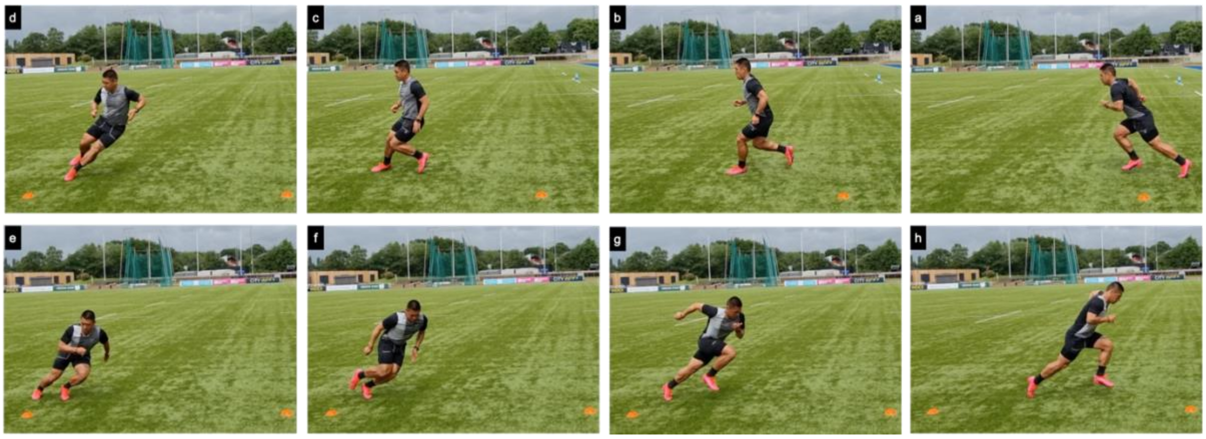


Figure 2. Agility schematic, whereby our focus will be on physical and technical skills (29).

Before an athlete can string together a series of complex athletic actions that we would describe as proficient CoDS, we must first train the constituent parts in isolation; that is, develop the athlete's acceleration, top speed, deceleration, and turning mechanics. Similarly, before we can teach mechanics that require turning > 60 degrees (11) and thus require the athlete to reduce their approach velocity, such as the cut or crossover (Figure 3), we would need to teach deceleration, while concurrently developing acceleration and top speed. Figure 4 outlines a series of drills to teach a 180-degree CoDS, focusing on the cut and cross-over step, with the drills progressing from teaching acceleration mechanics. This CoDS movement was chosen as it is relatively physically demanding. If an athlete can complete this, they are likely to have the physical capacity to undertake (or at least facilitate the development of) many other agility based tasks.



3a-h. Sprint toward target (at top speed). Final deceleration step made by inside/left leg, concurrent to realigning the body to turn 180 degrees. Outside/right leg "bounces" off ground, while inside leg pushes into the ground to reaccelerate. Outside leg completes the crossover step, putting the athlete back into an optimal position to accelerate

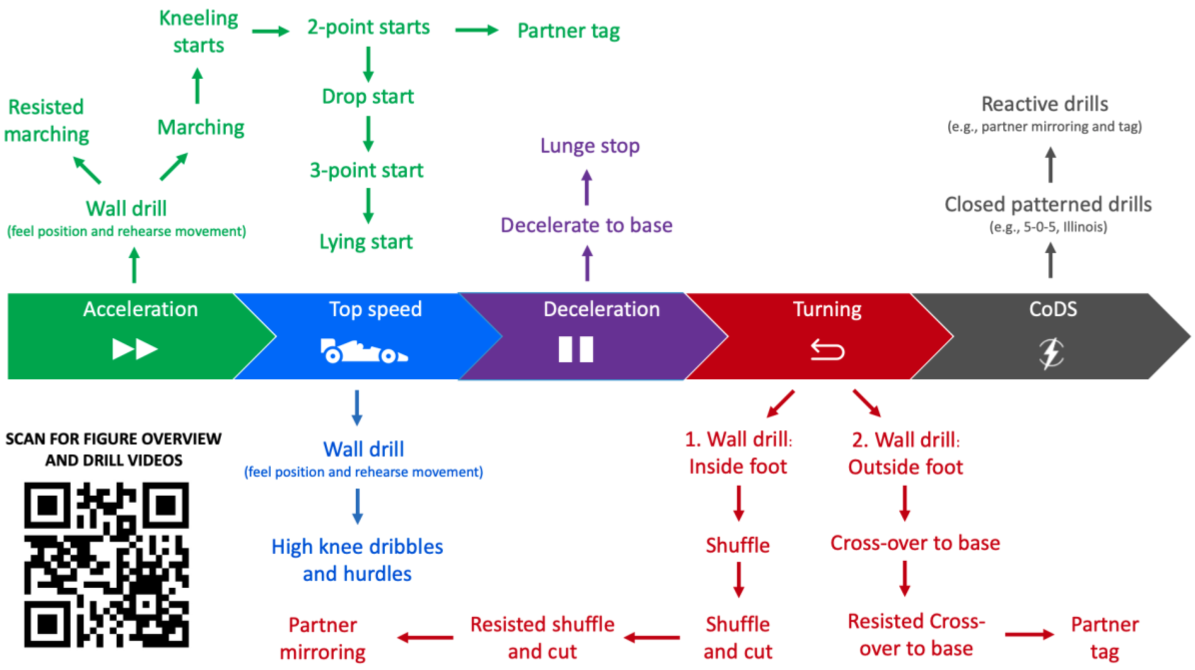


Figure 4. Progressive change of direction speed (CoDS) drills.

The Stretch Shortening Cycle

The motor skills above are positively affected by an athlete's stretch shortening cycle (SSC) ability (2, 10). Efficient mechanics lead to better storage and reutilization of elastic energy, which allow for enhanced force capacity and/or more economical movement, resulting in improved performance (31). On one hand, to push against the ground and generate high propulsive forces would be essential during acceleration, while plyometric ability or reactive strength would increase in significance as we approached top speed as the movement becomes more cyclical, with a greater need to convert potential (as opposed to chemical) energy into kinetic energy (31). We can crudely separate these two SSC modes based on ground contact time (GCT), as slow SSC mechanics (GCT > 250 ms) and fast SSC mechanics (GCT < 250 ms), respectively (31). Slow SSC mechanics are visually noted by increased flexion at the hips, knees, and ankles, resulting in a visible lowering of the athlete's center of mass (CoM). This may be to accommodate large negative acceleration forces, or to generate greater displacement, thus work, and propulsive power (33), but all resulting in a longer GCT. With fast SSC mechanics, the athlete aims to maintain leg stiffness (i.e., minimal joint flexion at ground contact) through antagonistic co-contraction, ensuring stretch is optimally induced at the tendon, minimal energy is lost as heat, and thus kinetic energy output is maximized (31). Figure 5 outlines progressions for the development of an athlete's SSC ability.

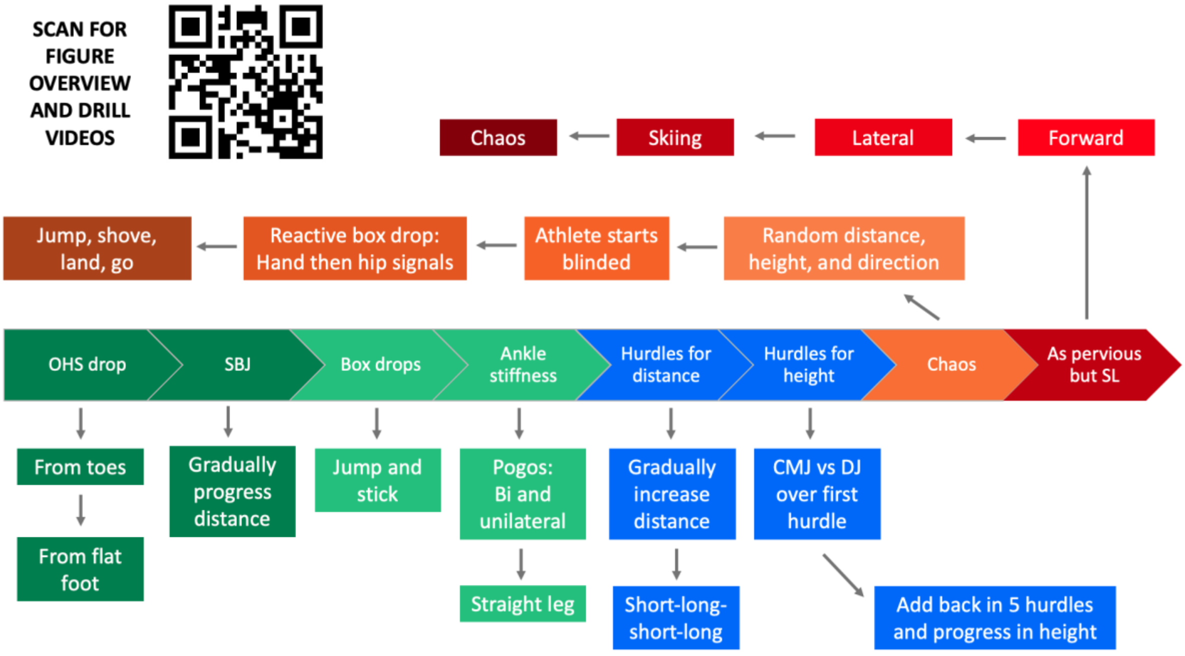


Figure 5. Progressive SSC drills. *OHS drop* = the athlete starts in an overhead squat position, before dropping rapidly into the base position. *SBJ* = standing broad jump, where the athlete rehearses and feels the contrast of soft (compliant) landings where the focus is on the dissipation of forces. *CMJ* = countermovement jump, *DJ* = drop jump, and *SL* = single leg jump. *Athlete starts 'blinded'* means that until the athlete turns and faces the hurdles, they have no idea what to expect – they must immediately go and figure out the best solutions while they complete the task. *Reactive box drop* = the athlete steps from the box at which time the coach will move and the athlete must position appropriately at landing to give chase. *Jump, shove, land, go* = athletes jump and bump in mid-air, before landing and traveling in a predefined then unscripted direction.

Strength and Power Training

While SSC mechanics can be improved by training with drills that incorporate this mechanism (e.g., the plyometric jumps seen in Figure 3), much like CoDS, it can be improved further by training its constituent parts (4). In the case of slow SSC mechanics, this entails focusing on propulsive force production, which would increase work (noting displacement is relatively fixed), resulting in increased power output and thus jump height or distance for example (33). In the case of fast SSC mechanics, an increase in force capacity would give the athlete the requisite strength to tolerate the eccentric or braking phase, and facilitate the disinhibition of the GTO, collectively resulting in the maintenance of leg stiffness (31). Finally, given these athletic movements occur over short time frames (typically < 300 ms), rate of force development (RFD) is key to performance and is trained using ballistic exercises of varying loads (4, 34). Ballistic training aims to improve athlete movement velocity under external load, which again, is ultimately underpinned by an athlete's maximum strength. Therefore, SSC mechanics are best developed when an athlete is deemed as powerful (i.e., can generate high forces at high velocities), and in turn, power is best developed on a foundation of strength (28). Accordingly, Figure 6 outlines progressions for the development of an athlete's strength and power capacity. This schematic uses the force-velocity relationship to example relevant exercises that may be used, noting that load will ultimately dictate an exercise's position on the continuum, but some exercises may suit heavy or light loads more than others (27). Furthermore, while many exercises can contribute to this phase, weightlifting derivatives have been predominately used due to their utility in overloading the triple extension pattern, while concurrently exposing the athlete to decelerating the system during landing/catching phase. In addition, it has been posited that the utilization of the stretch reflex is a contributing factor to the high-power outputs exhibited through weightlifting movements (19), and this may accentuate the stimuli for enhanced CoDS.

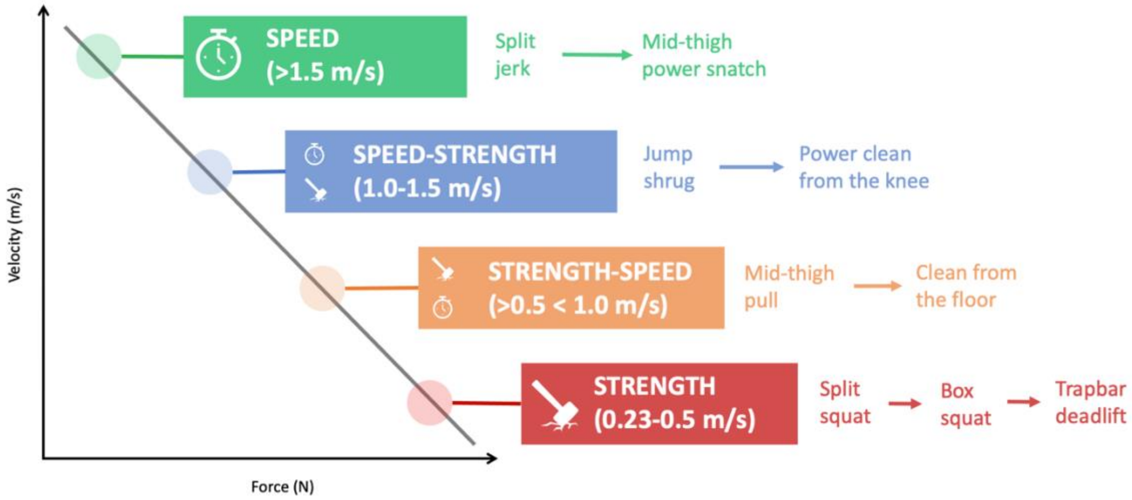


Figure 6. Progressive strength and power drills. This schematic uses the force-velocity relationship and barbell velocity to example relevant exercises that may be used, noting that load will ultimately dictate an exercise's position on the continuum, but some exercises may suit heavy or light loads more than others. The barbell velocities noted in this figure are just an example and may vary across devices and methods. *STR* = strength and *SPD* = speed.

Inevitable Imbalances

Athletes seem to inevitably develop movement compensations because their sport (as well as their habitual lifestyle) favors a particular set of movement patterns. Repeated exposures and accumulation of training and competition external loads can result in agonist muscles being stronger than antagonist muscles. Inter- and intra-limb differences are therefore often a product of competing in any single sport over time (14). If these muscle and between-limb imbalances are not addressed, performance may eventually be compromised as well as joint integrity, potentially leading to injury (12, 21). Common sites of such imbalances in the lower limb that relate to CoDS, across many sports, include the hip and knee musculature. Therefore, proactive measures to manage these observed deficits are warranted.

For example, and with regards to the hips, the modified Thomas test is frequently used to assess an individual's hip extension range of motion (37), with previous research highlighting it is a valid and reliable assessment, if pelvic tilt is controlled for (35). With the hip flexor group (e.g., iliopsoas, tensor fascia latae, rectus femoris) often displaying signs of over-activity (i.e., being more comfortable in a hip flexed posture), this reduces an athlete's ability to utilize the gluteal and hamstring muscles to their full capacity, noting that they are primarily responsible for hip extension movements. Thus, regular static flexibility around the hip flexor group may be a viable and easy method of enhancing range of motion in a commonly over-active region of the body. When coupled with isolated exercises (e.g., glute bridges or hip thrusts) and more compound-based movements (e.g., squats and split squats – which can target hip extensor strength while simultaneously stretching the hip flexors), both the over- and under-active muscles around the hips can be targeted, improving our chances of restoring optimal length-tension relationships between agonist and antagonist muscle groups. This then provides a safe foundation for sport-specific CoDS drills to be performed, remembering that our focus here is on the improvement of agility performance.

Strength of the knee musculature must also be considered when examining deceleration and CoDS due to the large braking forces involved. The quadriceps muscles play an important role in sudden deceleration (15). In female soccer players, those with a greater knee extension strength have been shown to decelerate more rapidly in the approach steps prior to the turn, resulting in faster approach velocities and CoDS (18). Eccentric knee flexor strength also facilitates the production of hip extensor torque to maintain trunk position and control of knee flexion (18). Thus, hamstring:quadriceps (H/Q) strength ratios are commonly measured by dividing hamstrings and quadriceps peak torques. A ratio > 0.6 has been recommended (8) and values above this have been indicated as a marker of improved intra-limb muscle strength balance. Other authors suggest a wider variety is expected with ratios dependent on test mode and population sampled (8). However, the load a joint will experience is dependent not only on the maximal capacity of involved muscles to produce torque, but also the magnitude of torque production when the muscles are at the same respective angle. The peak torque generated by the flexors and extensors are ~ 30º and 60º respectively and H/Q ratios can exceed 1.0 when the knee is closer to extension (3). Thus, when considering H/Q muscle balance using peak torque values, angle specific ratios should also be optimized, particularly in key positions that relate to mechanics of the desired CoDS task. Angle-specific neuromuscular adaptations (24) and changes in peak torque (1) have been shown at both short and long lever lengths. Therefore, in addition to resistance training that encourages force production through the entire

ROM at a range of velocities, it may also be prudent to train in partial ranges of motion and perform isometrics with the knee in different positions.

Mobility, stability, and form

When training our athletes under high loads, with high velocities, naturally we want them to move with efficient technique, ensuring the appropriate distribution of load across the musculoskeletal system. However, mastery of technique cannot be gained solely through coaching cues and feedback. Instead, athletes may have to be screened to identify their deficiencies in ROM as well as joints that exhibit poor motor control through a reduced stimulation from synergistic muscles. Naturally then, athletes must first be screened, initially identifying movement competency in a given task and if needs be, ROM through isolated joint testing thereafter. This order is proposed to determine whether movement competency can be enhanced through coaching and feedback to the athlete, or whether restricted mobility may be contributing to the process of reduced movement quality (17). Furthermore, screening allows practitioners to further individualize an athlete’s training program. Earlier in our example, strength was evidenced as a key physical quality to develop as a pre-requisite for power and RFD development, and as shown in Figure 6, numerous exercises can be programmed to develop this. Screening serves as a filter enabling us to determine whether the athlete is ready for additional loading in the weight room, and which movement patterns can be performed in the presence of existing limitations (17). For example, an athlete who struggles to gain sufficient depth in a squat screen may initially benefit from split squats and trap bar deadlifts in their program, so that strength adaptations can be enhanced, all the while mobility restrictions are worked on. Furthermore, if ankle mobility is considered the primary factor in this movement fault, then split squats with a short stance may be the primary choice, as this exercise will increase strength while encouraging the knee to move in advance of the toe, and thus simultaneously driving improvements in ankle mobility under load. Similarly, an athlete who exhibits a knee-dominant squat pattern that is deemed excessive may benefit from box squats, providing them with physical cues to ‘sit back’ and utilize their hips better during squatting (7). Equally, understanding joint loading across each variation, may determine that the front squat, which preferentially loads the knee extensors (38), is currently not best suited to this athlete. Importantly, all squat based exercises will ultimately develop lower-body strength, but certain scenarios may encourage one to be programmed over the other, generating an individualized approach to an athlete's training program.

Although exercises such as squat patterns are often used for screening purposes (5, 6, 7), Figure 7 outlines the process that practitioners can follow for any exercise that they deem worthy for assessing movement competency, as long as it enhances our understanding towards the over-arching performance goal. Figure 8 shows the process of using a specific screen to highlight movement competency and breakout assessments for joint ROM, based on movement dysfunctions that cannot be corrected from simply coaching the athlete.

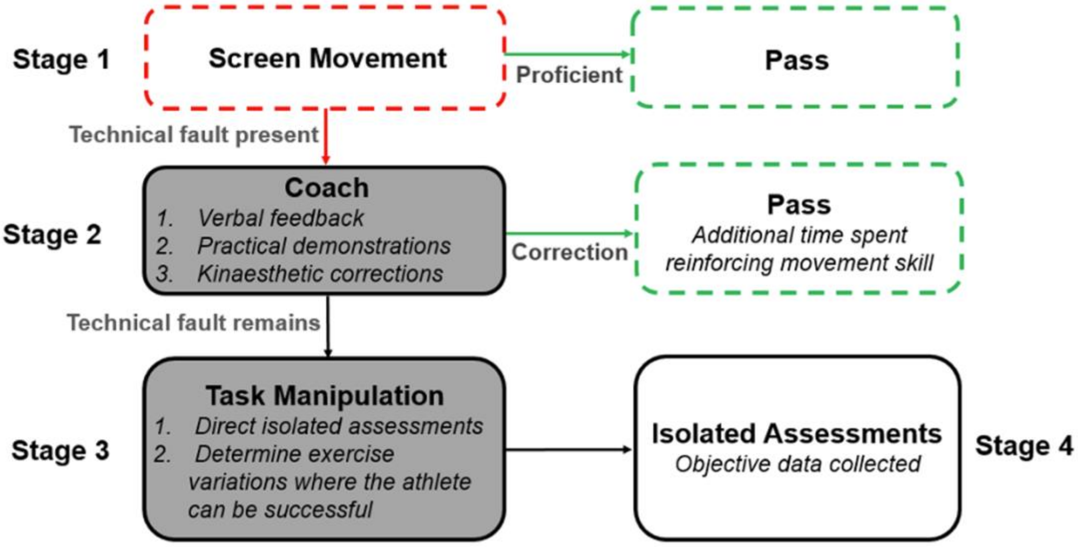


Figure 7. Step-by-step process for assessing movement competency and joint range of motion (if required) for any exercise (17).

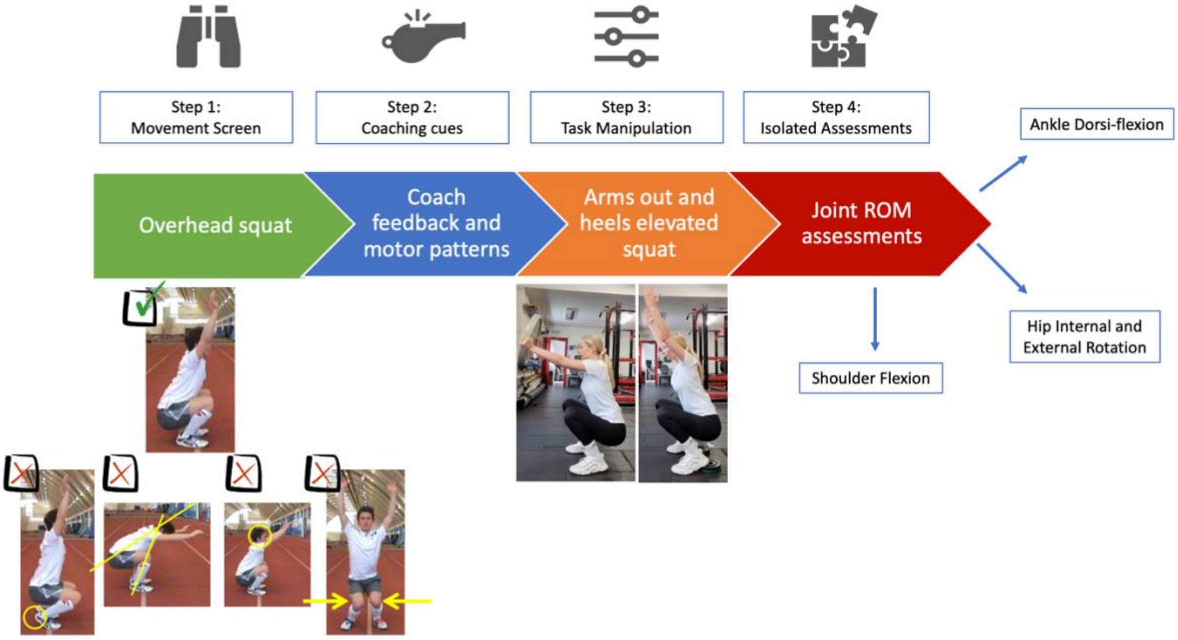


Figure 8. Step-by-step process for how this theoretical example could work for the overhead squat assessment, with an athlete exhibiting an excessive forward lean and lack of depth in the movement. When an athlete exhibits a lack of depth and/or an excessive forward lean, practitioners should aim to determine whether improvements in motor patterning can be coached or whether further assessments are required. Assuming this athlete exhibits no major improvements in squat technique from coaching cues, practitioners may consider *task manipulation*. Performing the ‘arms in front’ or ‘heels elevated’ squat, enables practitioners to determine if technique can be improved as a result of altered center of mass or by providing ‘free dorsiflexion’. Any improvements in technique may demonstrate that additional range of motion at the ankle and/or hips would be beneficial. Coaches can then corroborate this information objectively, via *isolated joint range of motion assessments*. These may help to determine whether deficits in range of motion exist at key joints in the kinetic chain, preventing optimal technique from being achieved in the initial movement competency assessment; which in this example, is the overhead squat.

Reasoned roadmap using reverse engineering

The theoretical or biological basis for how we move and respond to exercise stimuli, coupled with an understanding of how these are best sequenced such that one stimulus and subsequent adaptation can potentiate the next, is a means of devising effective and efficient training plans. Such an approach likely gives our athletes the best chance of attaining their goals. Figure 9 outlines the road map to effective CoDS as outlined in this article. The next stage then would be to converge this plan with that of those devised around nutrition and conditioning for example, as well as technical and tactical training, noting some compromise is inevitable given the multifactorial nature of sport performance. Equally, the final plan must be managed according to the available time and the strengths and weaknesses of the athlete.

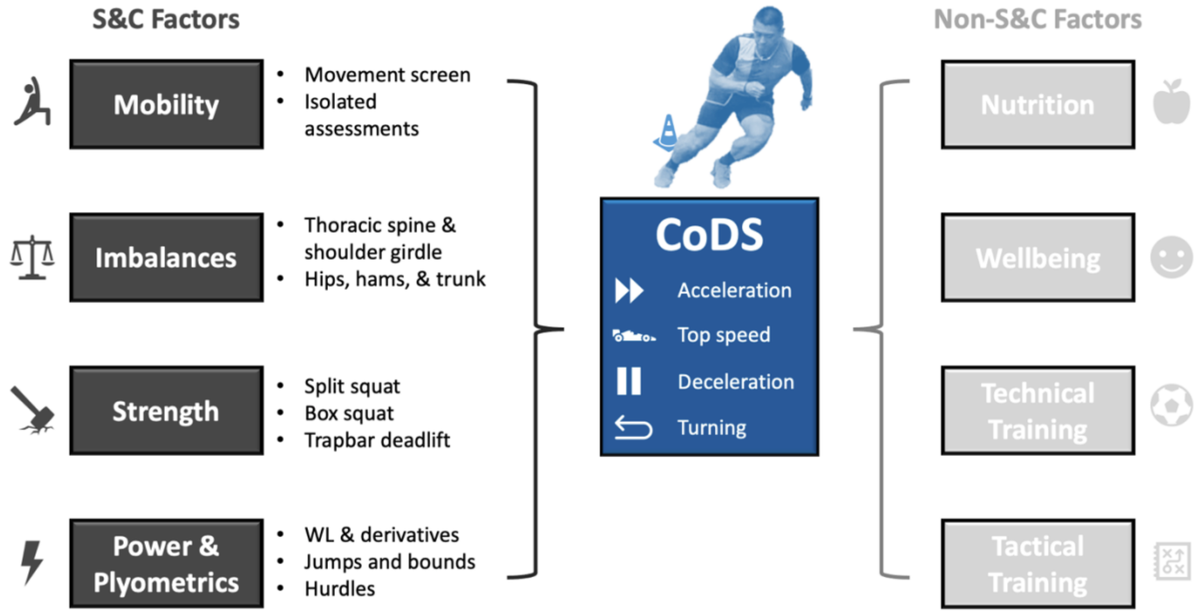


Figure 9. The strength and power based road map. This must be overlayed with those devised around nutrition and conditioning for example, as well as technical and tactical training, noting some compromise is inevitable given the multifactorial nature of sport performance. Following this convergence, the athlete will have a high-performance roadmap based around pre-defined key performance indicators. *SP* = split, *SQ* = squat, *TBDL* = trapbar deadlift, *BL* = bilateral, *UL* = unilateral, *BB* = barbell, *WL* = weightlifting, and *CoDS* = change of direction speed.

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