## Title

A Biomechanical Comparison of Accelerative and Maximum Velocity Sprinting: Specific Strength Training Considerations

## Authors

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## Overview

A large amount of published literature exists reporting biomechanical aspects of discrete phases within a sprint. This article initially identifies and discusses some of the key differences between accelerative and maximum velocity sprinting, before considering the implications these differences may have when constructing a strength and conditioning programme to develop the different phases of linear sprint running. Example exercises which could be used during the specialised preparatory and developmental phases of training are then proposed based on the discussed biomechanics and the available research related to these exercises.

## Introduction

Numerous biomechanical research studies have been conducted in both accelerative (e.g. [45,46,47,48,49,84]) and maximum velocity sprinting (e.g.[5,16,57,69,96,97]). Whilst there clearly exists a relative wealth of biomechanical data regarding these phases of sprinting, the differences between them are seldom discussed. Although accelerative and maximum velocity sprinting have not been directly assessed within a single cohort of athletes, general similarities such as the triple extension (proximal-to-distal hip, knee, ankle sequencing) can clearly be identified from the aforementioned research. However, both subtle and gross differences can also be identified between accelerative and maximum velocity sprinting from this existing literature. These include differences in the basic temporal and kinematic factors such as step length, step frequency and flight and contact times, the magnitude and direction of the forces generated against the ground during stance, and the kinematic and kinetic patterns exhibited by the ankle, knee and hip joints.

From a practitioner's point of view, different methods of training can be utilised to either increase the rate of acceleration or the ability to attain a higher maximum velocity. An understanding of the relevant biomechanical differences between accelerative and maximum velocity sprinting would allow the strength and conditioning coach to select appropriate exercises during specific training periods that best replicate both the observable kinematics as well as the causative kinetics at each joint. A greater understanding of these two phases could potentially allow the coach to focus directly on improving one phase, or potentially to concurrently improve both to the greatest possible extent without negatively influencing one or other of them. The aim of this article is therefore to identify and discuss some of the key temporal, kinematic and kinetic differences between accelerative and maximum velocity sprint running from published literature, and to consider the implications these variations may have when constructing a S&C programme to develop the different phases of linear sprint running. While there is evidence to suggest that the upper limbs play a part in sprint running performance, [,41,42] their contribution is largely a response to that of the lower limbs [7,39,59,60,73]and will not be focussed on in this article.

**Ground contact times**

Previously published data show that as a sprint progresses, ground contact times tend to decrease (Table 1). Data from international level sprinters[4] show clear differences between mean contact times during the first four steps (0.196, 0.179, 0.164 and 0.152 s, respectively) and those at maximum velocity (0.111 s). Salo, Keranen and Viitasalo (2005)[84] also observed contact times to decrease during the first four steps (0.200, 0.173, 0.159 and 0.135 s, respectively), and Čoh and Tomazin (2006)[19] confirmed that these continue to decrease over the first 10 steps (Table 1). Aside from the research of Atwater (1982),[4] there exists limited data from individual athletes during both acceleration and maximum velocity. However, Atwater's (1982)[4] data are comparable to those observed by researchers investigating early-acceleration, mid-acceleration or maximum velocity in isolation (Table 1), reinforcing the notion that contact times show a gradual decrease as an athlete continues to accelerate up to maximum velocity. Such temporal differences may therefore clearly be an important consideration to the S&C coach when selecting specific exercises to develop the different phases of a sprint.

****TABLE 1 NEAR HERE****

*Acceleration*

During the acceleration phase, ground contact times typically range between 0.12 and 0.20 s (Table 1) with the early and late stages of acceleration at the higher and lower end of this range, respectively. Longer ground contact times clearly allow an athlete more time to produce force. This allows greater impulse to be produced (impulse is the product of force and time, and directly determines an athlete's change in velocity), and would thus appear advantageous for performance.

However, the ultimate aim of any sprint is to cover a specific horizontal distance in the shortest time possible and thus it may not be favourable to achieve increases in impulse through simply increasing contact time. Better sprinters have been found to minimise contact times, allowing stance to be terminated prior to full extension of the leg joints and thus making recovery as efficient as possible during the swing phase.[61] Whilst this ability may be related to greater strength in these faster sprinters, it would still appear that for any given sprinter, greater joint extension towards the end of the stance phase where force production will be low is not beneficial due to the poor configuration of the muscles surrounding these joints for producing force.[51] Further research is required to investigate this issue, since it may be possible that an optimal contact time exists during acceleration: one which is sufficiently long to allow athletes to produce large forces, without being so long that contact times are extended beyond the time during which large forces can be produced.

*Maximum velocity*

Ground contact times at maximum velocity have typically been found to range between 0.09 and 0.12 s.[4,55,60] They are seemingly related to maximum velocity sprint performance, as research has shown that between sprinters, a reduced contact time is associated with greater horizontal velocity.[4,60,96] Weyand, Sternlight, Bellizi and Wright (2000)[96] found that in subjects of different sprinting abilities, those who reached higher maximum velocities on a level treadmill spent less time in contact with the ground than those who reached lower maximum velocities, which is confirmed by findings from earlier studies.[4,59] Weyand et al. (2000)[96] also showed that both faster and slower subjects (maximum velocity range = 6.2 to 11.1 m/s) required a flight time of approximately 0.13 s to be able to adequately reposition the legs for the next step. The differences in maximum stride frequency (range = 1.8 - 2.4 Hz) between fast and slow runners resulted entirely from the contact portion of the stride being shorter in faster runners. Although some participants in this study were classed as "physically active" and would not appear to be representative of more elite level athletes, and data were collected on a treadmill which may differ from overground running,[31,82] reducing ground contact times at maximum velocity is likely to be key for athletes at all levels to increase maximum velocity sprint performance. This is reinforced by the data of Mann and Herman (1985;[60] Table 1) which show flight times for elite athletes to be the same as those "physically active" subjects used in the Weyand et al. (2000)[96] study. The S&C coach therefore ought to seek appropriate ways to enable an athlete to minimise ground contact times at maximum velocity, without hindering their performance. How shorter ground contact times are achieved is a challenge of causality to the S&C coach, however: does less contact time allow an athlete to sprint faster or is a shorter stance phase a function of sprinting fast? An understanding of this issue will affect the strategies adopted to reduce ground contact times during maximum velocity, and will be revisited in subsequent sections in this article.

**Ground Reaction Forces**

Although ground contact time is clearly an important performance variable, it is also paramount that athletes generate large forces during these ground contacts to produce sufficient impulse to overcome inertia and gravity, and thus achieve high levels of performance. However, the magnitude and direction in which these forces are applied appears to differ as a sprint progresses. Since forces are ultimately the underlying cause of movement, be it in sprinting or any other form of locomotion, a greater awareness of how these forces are produced will enable the S&C coach to have a much better understanding of accelerative and maximum velocity sprinting, and thus be more informed regarding exercise selection for training.

*Acceleration*

Data from selected research studies (Figure 1) demonstrate that as the net horizontal impulses decrease throughout the acceleration phase as an athlete approaches maximum velocity, the peak vertical forces increase. Horizontal impulse production (relative to bodyweight) has been shown to predict 61% of the variance in sprint velocity in 36 participants from a variety of sports during the mid-acceleration (16 m) phase of a maximal effort sprint.[47] In contrast, vertical impulse production at the 16 m mark was found to account for only 17% of the variance in sprint velocity. Caution must be given when interpreting these data as direct causation cannot be assumed since sprint velocity at 16 m is a product of sprint performance over that entire distance, whereas the ground reaction forces at 16 m are those of a single stance phase. However, Hunter, Marshall and McNair (2005)[47] speculate that during the acceleration phase of a sprint, the most favourable impulse profile is one in which sufficient vertical impulse is generated to overcome gravity and create a flight time long enough for repositioning of the lower limbs, whilst all other strength reserves are applied horizontally in order to maximise acceleration.

****FIGURE 1 NEAR HERE****

In addition to the progressive changes in the demand for increased vertical force as the acceleration phase progresses, the effects of horizontal braking forces become greater throughout this phase. Horizontal braking impulses have been shown to increase threefold from -1.5 Ns (equivalent to a 0.02 m/s reduction in velocity for the subject studied) in the first step of a maximal effort sprint from blocks to -4.8 Ns (-0.06 m/s) in the fourth step.[84] By the 16 m mark (approximately step 10-11) mean braking impulses have been found to reach to reach -7.2 Ns (-0.10 m/s).[47] Although these findings are not directly comparable, they suggest that braking impulses continue to progressively increase as a sprint progresses. During the initial steps, this appears to be largely due to an increase in the peak horizontal braking forces generated – Salo et al. (2005)[84] observed mean peak braking forces of -215, -348, -421 and -672 N in steps one to four whilst the absolute mean braking phase durations were 0.012 (6.0% of total stance), 0.014 (8.1%), 0.012 (7.5%) and 0.013 s (9.6%). However, as the acceleration phase continues to progress, the duration of the braking phase increases and by the time maximum velocity is reached it has been found to last for 0.048 s (44%) of the stance phase.[69]

In addition to these increases in the amount of deceleration experienced during early stance, there also exists a gradual reduction in the subsequent increase in velocity (due to positive horizontal impulse) achieved during the remainder of the stance phase as the acceleration phase progresses. Salo et al. (2005)[84] found propulsive impulses to decrease from 93.5 Ns (+1.18 m/s) to 49.1 Ns (+0.62 m/s) between steps one and four of a maximum effort sprint. By the 16 m mark, propulsive impulses were found by Hunter et al. (2005)[47] to have reduced to 25.2 Ns (+0.35 m/s). The overall net propulsive horizontal impulses (positive propulsive minus negative braking) therefore progressively decrease throughout the acceleration phase as a result of both an increase in the negative braking impulses and a decrease in the positive propulsive impulses. Once the positive propulsive impulse equals the negative braking ground impulse (and the small braking impulse due to air resistance), the athlete is thus sprinting at constant (i.e. maximum) velocity.

*Maximum Velocity*

Since the velocity of the centre of mass does not change between successive steps once maximum velocity is reached and maintained (provided enough horizontal force is applied to the ground to overcome the effects of air resistance and horizontal braking forces) the rest of the applied force is directed vertically to overcome the effects of gravity in order to maintain maximum velocity.[96] It would therefore appear that the desired ground reaction force orientation changes from more horizontal to vertical as a sprint progresses, and that the magnitude of the horizontal braking force gradually increases (Figure 1). In the study by Weyand et al. (2000),[96] it was found that the participants able to reach higher speeds were able to express higher peak vertical forces (relative to body mass). This enabled them to develop the necessary vertical impulse to overcome the effects of gravity and thus ‘rebound’ off the ground more quickly, clearly relating to the shorter ground contact times discussed previously. Weyand et al. (2000)[96] therefore suggested that by applying greater vertical forces during maximum velocity sprinting, faster runners are able to achieve the effective impulses and flight times necessary to reposition their swing legs with shorter contact times. This reduction in ground contact times due to the greater vertical forces applied by faster runners results in increased stride frequencies without a concurrent decrease in stride length.[96] It would therefore appear that increasing lower body strength and the rate at which it is produced would be an appropriate strategy to decrease ground contact times during maximum velocity sprinting, whereas simply instructing an athlete to reduce their ground contact time would most likely result in the sacrifice of force production and stride length, and ultimately sprint performance.

## Kinematics at touchdown

Whilst considering the horizontal and vertical force components separately is important since it can clearly aid the understanding of sprinting, they are part of a single ground reaction force vector and thus cannot be independently altered. The direction in which the resultant force vector acts is largely dependent on body position and the muscles being activated.[54] Different lower limb joint angles and trunk orientations at touchdown will affect the horizontal distance between the centre of mass and toe at touchdown, a variable that has been termed touchdown distance.[47] Differences in body configuration at touchdown and thus throughout the stance phase could clearly be of consequence to exercise selection for the different sprint phases. Since the majority of the energy needed to reposition the limbs during the swing phase appears to be provided by passive mechanisms of energy transfer rather than muscular power,[60,96,97] the kinematic factors relating to the stance phase will form the primary discussion in this section.

### *Acceleration*

During all steps within a sprint, the ankle initially dorsiflexes after touchdown, before plantarflexing for the remainder of stance.[6,48,50] In the first step of a sprint, this transition from dorsiflexion to plantarflexion has been found to occur at approximately 30% of stance[6] whilst by mid-acceleration (14 m) it occurs at around mid-stance.[50] The knee and hip joints typically extend from touchdown onwards during both early and mid-acceleration,[6,48,50] and for some athletes the knee starts to flex just prior to toe-off.[6,48,50] One interesting observation during accelerative sprinting is that the centre of mass must be rotated forward about the stance foot prior to rapid extension of the stance leg.[48] If the leg was to extend at the point of touchdown the centre of mass would be directed in a more vertical direction and, as already highlighted, the aim during acceleration is to propel the centre of mass horizontally. Therefore, at the beginning of the stance phase it is this rotation that contributes to forward motion, whereas later on in stance rapid extension of the leg joints facilitates further forwards acceleration since the athlete is in a more favourable position for directing their leg extension force horizontally.

It is possible to reduce this need to rotate the centre of mass in front of the stance foot by repositioning the foot further back relative to the centre of mass at the point of ground contact, thus achieving a greater negative touchdown distance (i.e. the CM further ahead of the foot). Touchdown distance has been found to gradually increase as a sprint progresses (i.e. the CM becomes progressively further behind the foot at touchdown; Table 2), and has previously been related to the magnitude of the braking impulse generated during stance in accelerative sprinting (16 m), with foot placement further in front of the body related to higher braking impulses.[47] It appears that keeping the foot behind the CM at touchdown during early acceleration (and restricting how far in front it is placed during mid-acceleration) may help to facilitate performance, although it is possible that this may only be true to an extent since placing the foot too far behind the CM during early acceleration could leave the leg in a less favourable position for producing force, thus leading to lower levels of performance.[6]

****TABLE 2 NEAR HERE****

*Maximum velocity*

During maximum velocity the ankle and knee joint angles typically reduce for the first 60% of the stance phase whereas the hip joint continues to extend throughout the entire phase,[5] similar to its movement during acceleration. During maximum velocity, the foot touches down in front of the centre of mass (positive touchdown distance), with values of up to 40 cm reported (Table 2).[3] In attempts to reduce ground contact times and horizontal braking impulse while maximising propulsive forces coaches commonly use ‘paw back’ drills to bring the foot further back relative to the centre of mass. However, simply minimising large touchdown distances could potentially just result in a decreased stride length unless an athlete is strong enough to achieve the vertical force production required during the ground contact phase. Consequently, when looking to reduce the extent to which an athlete’s foot is forward of their centre of mass upon touchdown the S&C coach should determine whether strength or technique factors are limiting the athlete’s ability to do so without sacrificing stride length and overall velocity.

**Joint kinetics**

The kinematics at touchdown and during stance provide an accurate description of the movement patterns used during sprinting, however, knowledge of the underlying kinetics are required for a more complete understanding of the movement. These kinetics are calculated using inverse dynamics analyses which allow the *resultant* joint moments and powers to be determined (i.e. the net effect of all muscles crossing that joint). Phases of power generation and power dissipation can therefore be identified for the flexor and extensor muscle groups crossing each joint. For example, whilst a joint may be extending throughout stance, the muscles surrounding that joint may not be acting to extend that joint, but are actually exhibiting a power dissipating (net eccentric) flexor moment to slow the rate of extension, as is the case at the hip prior to toe-off. Although it is acknowledged that individual muscle characteristics are unknown, the terms *net concentric* and *net eccentric* will be used when referring to these respective phases of power generation and dissipation about different joints throughout this article. Identifying the basic differences in the kinetic patterns associated with the muscle activity surrounding the hip, knee and ankle during different phases of sprinting can therefore allow the S&C coach to better select exercises specific to the relevant joint kinetics required for each phase.

*Ankle*

The muscles surrounding the ankle joint create a plantarflexor moment throughout the entire stance phase. Following foot strike, this resultant joint moment helps to reduce the negative vertical velocity of the body through power dissipation (net eccentric contraction) about the ankle for approximately 30% of stance during early acceleration,[6,48] 50% during mid-acceleration[50] and 60% at maximum velocity.[5] Once this has been achieved and the dorsiflexion has ceased, the plantarflexor moment then generates power (net concentric contraction) to extend the ankle joint and help propel the body into the subsequent flight phase. During early-acceleration, the total work due to power dissipation at the ankle joint during early stance is less than the subsequent power generated done by almost a factor of 3.[6] By mid-acceleration (14 m) these appear to be roughly equal (i.e. a factor of 1),[50] whereas during maximum velocity this factor has been found to drop to around 0.6[5] with the ankle plantarflexors dissipating more energy than they are generating (i.e. doing more net eccentric than concentric work). There is therefore clearly a larger power generating (net concentric) emphasis at the ankle joint during early-acceleration compared to maximum velocity. This may be due to the reduced horizontal braking and vertical impact ground reaction force peaks during early-acceleration as well as the increased time available to generate force, although additional research is required to investigate this further.

*Knee*

During early-acceleration, the knee typically continues to extend upon touchdown, although this rate of extension is sometimes slowed by the presence of the horizontal braking forces.[6] These forces are commonly associated with the presence of a net flexor moment at the knee joint in the first few milliseconds of stance during early-acceleration,[6,48] after which an extensor moment dominates for the remainder of the stance phase. Slightly more variable knee joint moment patterns have been observed during mid-acceleration[46,50] and maximum velocity,[5,62]although there is typically a knee flexor moment of greater magnitude during early stance as the phases of a sprint progress, likely due to the increasing influence of the braking forces. Due to these differences, the knee joint appears to be considerably more involved in net concentric activity during the earlier stages of acceleration, whereas as a sprint progresses the knee musculature has been suggested to adopt a more compensatory role.[5] In all stages of a sprint, the muscles surrounding the knee joint appear to switch to flexor dominance prior to toe-off in an apparent attempt to terminate ground contact and also due to the muscle sequencing involved in the biarticular transfer of power distally down the leg.[34]

*Hip*

Although the hip joint has typically been shown to extend throughout the entire stance phase during all accelerative and maximum velocity phases of a sprint[5,6,46,48,50,62] the resultant joint moments around the hip are variable across the literature. In all phases, a net extensor moment is present at the hip at touchdown, and the magnitude of this has been identified as being important to sprint performance at maximum velocity.[62] By toe-off this moment has changed to flexor dominance in order to reduce the rate of extension at the hip joint, but the time at which the dominance switches from extensor to flexor appears not to be dependent on the phase of a sprint, having previously been observed at around 70% of stance in the first two steps of a sprint,[6,48] ~50% at the 14 m mark;[50] and both ~60% and ~80% during maximum velocity (at 60 m).[5,46] Whilst this could be influenced by the accuracy with which these data can be determined using current inverse dynamics analyses (and the propagation of errors as the analysis progresses up the leg), it may be due to individual ability and differences in technique between the studied athletes. For example, hip extensor dominant athletes capable of producing more powerful contractions may require an earlier switch to flexor dominance in order to prevent the duration of the stance phase increasing.

The overall patterns observed in the joint kinetics are logical given the demands of sprinting, as greater power generation is required towards the start of the run to rapidly create velocity from an initial stationary position. With the exception of the kinetic activity at the hip, it would seem that there is a shift in emphasis from this power generating (net concentric) to power dissipating (net eccentric) activity as a sprint progresses. Eccentric work may therefore become increasingly important during mid-late acceleration and maximum velocity sprinting due to the larger peak vertical and horizontal braking forces experienced.

****TABLE 3 NEAR HERE****

**Strength Training Recommendations**

The kinetic and kinematic differences identified between accelerative and maximum velocity sprinting in this article (summarised in Table 3) suggest that if a S&C coach wishes to maximise the transfer of training effects to a specific phase of sprint performance, appropriate exercise selection is important. There are numerous strength training exercises which may be suitable to develop both phases of sprinting, some of which are highlighted in Table 4. Based upon Bondarchuk's (2006)[10] theories of training transfer, exercises for improving sprint speed can be classified in a hierarchy according to the degree to which they satisfy the principles of dynamic correspondence[87,95] for the skills of accelerating and sprinting at maximum velocity.

****TABLE 4 NEAR HERE****

*General Preparatory Exercises*

General preparatory exercises (GPE) such as those shown in Table 4 produce high forces against the ground (predominantly bilaterally) and are primarily used to develop neuromuscular adaptations such as motor unit recruitment and firing frequency.[36,52,71,72,75,86,98] These exercises are related to the ability to produce force through a triple extension (hips, knees and ankles) movement pattern.[12,24,26,38,41,99,102] Based upon this principle, it has been postulated that high force strength exercises such as squats and deadlifts and high force, high velocity explosive exercises, such as cleans and snatches, may induce neural adaptations which enable the athlete to recruit larger motor units more effectively for the similar movement patterns observed in sprinting.[14,35,67,77,99]

Clearly a wealth of information exists on these exercises and their associated benefits. It is beyond the scope of this article to provide a technical coaching model and rationale for each of these exercises so readers are referred to other literature (e.g.[11,22,232,76, 80,88,100,103,104,105]). Furthermore, as GPE do not necessarily closely replicate the kinematics of the skill being trained and therefore do not meet the principles of dynamic correspondence to a high degree, they are not the primary focus of this article. It is not until the specific preparatory periods of training that a S&C coach ought to select exercises bearing greater resemblance to sprinting to help direct the strength increases gained from GPE towards the patterns required. Due to a lack of evidence to support the use of some of the more specific exercises discussed in this article, it is important to note that the exercise selection guidelines for the different sprint phases given in Table 4 for the specialised and preparatory developmental phases are intuitive suggestions based on the previously discussed biomechanical comparisons to provide some examples of how such differences could be accommodated in training. More research is required to investigate the transfer of training of such exercises to performance in the different sprint phases, and to assess the extent to which these exercises satisfy the principles of dynamic correspondence. The aim of the remainder of this article is therefore to provide a rationale for utilising these exercises during the specific preparatory period of a sprint training programme.

*Specialised Preparatory Exercises*

While typical multi-joint lower-limb strength training exercises such as the squat are deemed appropriate for the development of strength during a general preparation phase, more specific preparation periods containing specialised preparatory exercises (SPE) should cater for the phase of sprinting being addressed.[28,32,53,81,107] During specific training periods it could be speculated that the strength exercises selected should have contact times close to and forces comparable to or higher than those in sprinting. Additionally, the above comparison of differences between phases would suggest that the exercises selected should also reflect the different directional force requirements between acceleration and maximum velocity. However, it is largely differences in body position (e.g. a larger positive touchdown distance – centre of mass initially much further forward relative to the foot at touchdown during acceleration) that allow an athlete to redirect their force production relative to the ground (i.e. globally) rather than a modification to the way the body operates within its local frame in terms of force production (i.e. a proximal-to-distal hip-knee-ankle triple extension is clearly evident in all phases[5,48,50]). This suggests that attempts to match an exercise to the directional force production requirements should take place through a change in body position so similar forces are generated from a closed kinetic chain pattern of movement.

The relatively short ground contact times during both acceleration and maximum velocity pose a challenge to the athlete. It has been shown that the temporal response to the development and transmission of muscular force *in vivo* to a single electrical impulse in human knee and ankle extensors in young adult males far exceeds the time available when running,[37] highlighting that it would be impossible to reach maximum force production during the stance phase. For this reason, it would appear that strategies to increase rate of force development should supersede those implemented to increase maximum strength during this phase of training.

Plyometric exercises are widely used by coaches as a means by which to increase the rate that force can be produced through an enhanced utilisation of the stretch shortening cycle (SSC),[13,93] as occurs in all stance phases of a sprint about the ankle.[5,8,50] The duration of contact will reflect the type of SSC function taking place. Schmidtbleicher (1992)[86] suggests that the SSC can be classified as fast if the contact times are less than 0.25 s and angular displacements of the hips, knees and ankles are small whereas a slow SSC comprises longer contact times and larger angular displacements. Although the understanding of the SSC mechanisms remains incomplete, different adaptations are likely to result from fast and slow SSC[9] and thus training with slow SSC may not be suited to activities that involve a fast SSC and vice versa. The ground contact times during acceleration and maximum velocity (Table 1) imply that a fast SSC occurs in both. However, there are clearly differences in contact time as a sprint progresses, and simply classifying all contacts into the same 'fast SSC' category may be misleading as contact times during early acceleration can be around double those observed during maximum velocity (e.g.[4]; Table 1). Where possible, exercises with contact times at the shorter end of the 'fast SSC' continuum should be selected for maximum velocity and the longer end for acceleration although in reality there may be few plyometric exercises where the ground contact times are less than 0.16 s.[101] However, the importance of force production and the rate at which it is developed must be accounted for, as it appears that faster sprinters are able to achieve higher velocities due to their ability to produce greater force in less time rather than simply spending less time in stance, and further research is clearly required to assess the direct transfer from plyometric exercises with different sprint-specific contact times to the different phases of sprinting. It is acknowledged that greater forces are produced during a number of plyometric exercises than in sprinting.[70] As a result, in exercises such as bounding and hopping where ground contact times are longer than those during sprinting, one could speculate that they are still likely to have a positive transfer effect due to the higher levels of force production and the similar leg extension patterns adopted. However, the greater the disparity between ground contact times in the sprint phase being developed and the plyometric exercises used, the less specific the exercise (and potentially the SSC used) will become. Furthermore, although a greater lower-limb eccentric demand during stance has been identified when sprinting at maximum velocity,[5] a SSC occurs at the ankle during all phases of sprinting, thus plyometric exercises would clearly be appropriate during acceleration as well as maximum velocity, and previous research has observed improved acceleration performance (over 40 m) following a plyometric intervention.[83]

The SPE listed as suitable to all sprint phases within Table 4 appear to provide a transition from GPE to more specific SPE and may be useful in the local rather than global reference frame of force production. Whilst there is limited research regarding some of these exercises, they do not correspond dynamically to a great extent to one phase or another but are suggested to have mechanical similarities to both phases of a sprint so can be classified as special preparatory exercises for developing sprinting performance. Exercises performed under loads which have a slow SSC component and relatively low eccentric actions such as a jerk exercise or a barbell squat jump may seem more suited to improving an acceleration phase of sprinting. However, as these exercises produce high vertical forces[33,44] it could also be argued they are also suitable for improving max velocity sprint speed.

The exercises suggested for the development of acceleration (Table 4) place an emphasis on the development of explosive concentric strength, previously identified as important during this phase. The medicine ball dive throw (Figure 2) incorporates the forward rotation of the centre of mass about the stance foot prior to leg extension, as identified during accelerative sprinting, to augment the horizontal production of force. Standing with feet in a staggered position with a medicine ball held to the chest, the athlete extends explosively at the ankle, knee and hip whilst ‘diving’ forward and projecting his or her body into the air, launching the medicine ball in a largely horizontal direction for maximum distance. For safety, a crash mat should be used for landing as illustrated in Figure 2. It is also advisable for athletes new to this exercise to practice the technique and executing a safe landing without any load before progressing to the full dive throw movement.

****FIGURE 2 NEAR HERE****

The standing long jump (Figure 3) would seem to be well suited to acceleration due to its low eccentric and high concentric demands, and the requirement for the athlete to move their centre of mass forward of their base of support prior to jumping in order to direct their leg extension forces (associated with the triple extension) more horizontally. Performing the exercise off one leg and hopping for distance will make the activity more specific to an acceleration phase (Figure 4).

****FIGURE 3 NEAR HERE****

****FIGURE 4 NEAR HERE****

High-load sled towing has been proposed to be a form of training that bridges the gap between general strength training and specialised developmental track-based conditioning.[49] This training method encourages an increased forward lean, as observed during acceleration as a result of the large horizontal ground reaction force production, as well as a unilateral triple extension pattern. The guidelines for loading of weighted sled towing, which appear later in this article, should be followed when resisted sprinting is purely being utilised as a special developmental exercise (SDE). The suggestion that training with weighted sleds and vests may elicit long-term alterations in sprinting technique which adversely effects sprint performance is purely speculation and unsubstantiated in the research literature. Resisted sprint techniques using higher loads are likely to alter sprint kinematics acutely[25,57,64,72], however higher loads may provide more general strength adaptations which will assist with the transfer of training from GPE. The influence of sprinting with loads higher than those currently suggested in the literature requires further research.

A major consideration for the S&C coach in regard to the type of exercises selected during maximum velocity specific training are the increased braking forces evident as a sprint progresses from early acceleration towards maximum velocity. The explosive power generating (net concentric) action of muscles about the knee and ankle during acceleration make way for greater eccentric strength demands which becomes increasingly important as velocity increases. This is due to the increased negative vertical velocity which an athlete must reverse upon contact, as evident by the increased power dissipation (net eccentric work) observed about the ankle and knee joints as a sprint progresses. The exercises suggested in Table 4 for the development of maximum velocity sprint running are typically characterised by vertical force production, smaller displacements at the ankle, knee and hip and a greater emphasis on power dissipation (eccentric strength) requirements when compared to acceleration.

Vertical depth/drop jumps (Figure 5) require large vertical forces[9] to be produced and emphasise a short SSC, thus appear to be well suited to maximum velocity sprint running. Traditionally the depth jump is performed bilaterally, which reduces the specificity of this exercise to sprinting. Single leg depth jumps are not often advocated due to the excessive force exerted unilaterally and long contact times. However, with a suitably low box height and reduced ground contact times, single leg depth jumps may be an appropriate method of training for maximum velocity for more advanced athletes (Figure 6).

****FIGURE 5 NEAR HERE****

****FIGURE 6 NEAR HERE****

Based upon typical flight times of 0.125 s in maximum velocity sprinting (Table 1) and simple equations of projectile motion, the vertical velocity of the centre of mass at touchdown would be achieved from a box height of 2 cm. This suggests that depth jumps from considerably greater heights actually place a much greater initial demand on the body to overcome the downward velocity when compared to early stance during maximum velocity sprinting. Whilst a box height of 2 cm is not necessarily a recommended box height it indicates that the ground reaction forces exhibited when the foot strikes the ground during maximum velocity sprinting are produced by more active means (due largely to hip extension) than the forces observed during a depth jump. For these reasons, hurdle rebound jumps (Figure 7) may be more appropriate to maximum velocity sprinting than depth jumps. Hurdle rebound jumps have a high eccentric loading phase and require considerable force production during ground contact. On the downward phase the athlete has to actively ‘strike’ downwards quickly in order to apply force to the floor in time to bring legs back up quick enough to clear the succeeding hurdle. Hurdle rebound jumps may be more favourable than a box rebound jump the athlete is often in a flexed position when jumping from the box and so full extension is not present on every other repetition.

****FIGURE 7 NEAR HERE****

The overhead medicine ball throw (Figure 8) is another exercise requiring largely concentric vertical force production through a triple extension pattern that may provide a link between GPE and max velocity sprinting.[10,66,90] Little research has been conducted into the optimal weight to utilise for medicine ball overhead throwing. Loads of around 7% of body mass have shown moderate correlations with peak power output as measured with a CMJ[66] with lighter loads (3kg) showing a much higher correlation.[90] It should be noted that these results are likely to be influenced by several factors including the anthropometric dimensions of the athlete, strength levels and degree of skill.[66] Heavier medicine balls (8-15kg) are likely to bring about adaptations which are more general in nature so when used as a SPE, the load of the medicine ball should be light enough (5-7kg) to allow a more rapid and explosive execution of the movement to improve the transfer of training to max velocity sprinting.

****FIGURE 8 NEAR HERE****

There are numerous exercises specific to either phase or appropriate for both phases, and therefore it is important to note that the exercises proposed thus far are suggestions based on the previously discussed biomechanical differences. However, discussion of these exercises clearly highlights the importance of considering the different demands within a sprint due to the different phases.

*Specialised Developmental Exercises*

SDE involve overloading the actual skill being trained by replicating the movement pattern and in doing so, make it possible to more effectively and selectively improve an element of the skill being targeted.[10] Any SDE should be used alongside and in conjunction with further execution of the actual skill being trained, usually within the same session, to reduce any potential for negative transfer of learning. A S&C coach has a limited number of exercises at their disposal when selecting SDE. Exercises which overload a mechanical element of a sprint phase should be selected with assisted and resisted sprinting and various plyometric bounding exercises suggested in the literature for improving sprint performance.[2,21,28,29,30,58,79,89,91,101,106]

Many different resisted and assisted sprint training methods have been investigated with the aim of improving the acceleration phase of sprinting.[1,28,58,79,89,91,106] Sled towing is one specialised developmental exercise for sprinting purported to lead to greater levels of adaptation by recruiting more muscle fibres through increasing the load on the leg extensors.[17,29] It is well established that resisted sled towing causes alterations to acceleration phase kinematics[58,65,,74] by acutely increasing stance time and angles at the trunk and hip resulting in an increased contact time during the first step of a sprint start[25,65] and inducing a more horizontal position during an acceleration phase.[58,74] Although sled towing sprint training is believed to increase lower-limb strength, there are concerns that the effects may not transfer to acceleration performance due to negative influences on acceleration kinematics.[49,58,] As a result, several studies have sought to determine the optimal load to utilise to minimise kinematic alterations to technique but maximise long term benefits to acceleration performance.[1,58,65,89] If sled load is too light stimulus to the neuromuscular system will be insufficient resulting in little change in sprint performance through this means,[89] but if resistance is too high, acceleration kinematics may be altered,[65] reducing the specificity of the exercise and the transfer of training effect. Data indicate that a load which represents 10% of body mass appears to have no negative effect upon kinematic variables associated with an acceleration phase[1,65,74] whereas loads greater than this begin to adversely affect technique.[65] Other authors have suggested loads of 5-10% body mass[74] and up to 32% body mass[58] may improve sprint performance. Similarly, it has been suggested that acceleration velocity should be decreased by no greater than 10% as a result of towing a load.[49] Previous authors[58,89] have proposed an equation to calculate the optimal load required for sprint training with a sled:

$$\% \text{ body mass} = (-1.96 \times \% \text{ velocity}) + 188.99$$

where % velocity represents the required training velocity as a percentage of maximum velocity (e.g. 90% of maximum). Although these recommendations offer some insight into the optimal load for sled towing, further research is required. There have been relatively few intervention studies that have examined the effects of sled towing upon sprint performance[17,39,86,90,102] with results showing acceleration velocity appears to improve as a result of sled towing sprint training compared to non-resisted sprint training but with max velocity remaining unaltered.[18,40,94,106] Other studies have found a period of sled towing training to be no more effective at improving acceleration than non resisted sprint training.[89]

Utilising weighted vests whilst sprinting has been suggested as a means of special developmental training to improve max velocity sprint speed.[2,18,25,85] Few studies have investigated the effect of weighted vest sprinting upon changes in sprint kinematics[2,25] and sprint performance after a period of training wearing additional load[18] with suggestions in the literature for prescription of training mainly anecdotal[28,29]. Increases in eccentric loading at ground contact causing higher braking forces and longer contact times have been shown to induce changes to sprint kinematics when vest loads are >15% of the athletes body mass[2,25], however there is currently no evidence that short exposures to loads heavier than this whilst sprinting causes alterations to sprinting kinematics long-term.

Both uphill and downhill running have been suggested to improve sprint performance.[20,27,79] Research is lacking on biomechanical alterations to sprint technique as a result of a gradient change, however it has been shown that sprinting up a 3$^{o}$ slope decreases velocity (3%), decreases step length (5%) and increases trunk flexion, effectively placing an athlete into a similar position to that observed during an acceleration pattern of sprinting.[56,78] Authors have suggested that hill incline should be of a gradient that does not compromise running form[27], although clearly this is open for interpretation. Guidelines for uphill sprinting in the literature are largely anecdotal[27,78,79] but it is recommended that slopes do not exceed 3$^{o}$. The chronic effects of this SDE compared to sprinting on a flat surface have yet to be investigated.

Bounding exercises have been shown to produce similar force-time characteristics to that of maximum velocity sprinting[70,101] and are performed unilaterally in a cyclical manner whilst generating high forces, which are observed by large hang/flight times when compared to sprinting at maximum velocity. For these reasons bounding exercises would appear to meet the principles of dynamic correspondence with respect to maximum velocity sprinting. The sprint or speed bound exercise referred to in Table 4 is simply an exaggerated sprint with an emphasis on completing the required distance as quickly as possible,[101] thus the distance covered with each 'step' is less than, and the stride frequency is greater than, in traditional bounding where height and distance are maximised without necessarily an emphasis on completing the required distance or number of steps as quickly as possible.

Minimal research exists comparing the biomechanical factors of unilateral based plyometric exercises to sprinting (e.g.[70,101]) or their transfer to sprint performance (e.g.[64,83]) with most studies in this area investigating bilateral plyometric exercises and their association with vertical jumping (e.g.[63,92]). With this in mind the S&C coach should logically select plyometric-based SDE based on the relevant research available and the related discussion points highlighted in this article.

**Conclusion**

In conclusion, there are clear biomechanical differences during the stance phase of acceleration and maximum velocity sprint running. Longer ground contact times exist during acceleration with a greater requirement for explosive concentric strength, directed more horizontally. Shorter ground contact times exist during maximum velocity with a greater requirement for reactive eccentric strength, and vertically directed forces. These relatively clear discrepancies can help inform the S&C coach in selecting exercises to improve either phase in isolation. Less clear, however, is the approach a S&C coach should take when looking to improve both speed qualities concurrently. Without a sound understanding of the biomechanical parameters involved in linear sprint running, a S&C coach may, at best, limit an athlete's horizontal velocity during acceleration and maximum velocity and, at worst, hinder their performance in either phase. More research is needed to ascertain the effects of different training modalities on the different phases of linear sprint running and whether training for one will have a detrimental effect on the other.

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## Tables

**Table 1. Contact and flight times published in previous sprinting research from various distances/steps within a sprint.**

| Stage of sprint: Step number | Stage of sprint: Distance (to nearest m) | Source* | Mean contact time (s) | **Combined stage mean for contact time (s)** | Mean flight time (s) | **Combined stage mean for flight time (s)** |
|---|---|---|---|---|---|---|
| 1 | - | [73] | 0.220 | **0.198** | 0.050 | **0.027** |
| | - | [84] | 0.200 | | 0.045 | |
| | 1 | [4] | 0.196 | | 0.063 | |
| | 1 | [19] | 0.177 | | 0.050 | |
| 2 | - | [73] | 0.180 | **0.173** | 0.060 | **0.061** |
| | - | [84] | 0.173 | | 0.058 | |
| | 2 | [19] | 0.159 | | 0.082 | |
| | 2 | [4] | 0.179 | | 0.043 | |
| 3 | - | [84] | 0.159 | **0.153** | 0.074 | **0.072** |
| | 3 | [19] | 0.136 | | 0.082 | |
| | 3 | [4] | 0.164 | | 0.060 | |
| 4 | - | [84] | 0.135 | **0.139** | 0.081 | **0.083** |
| | 5 | [19] | 0.131 | | 0.099 | |
| | 5 | [4] | 0.152 | | 0.069 | |
| 7 | 10 | [19] | 0.120 | **0.120** | 0.101 | **0.101** |
| 10 | 15 | [19] | 0.110 | **0.110** | 0.115 | **0.115** |
| - | 16 | [45] | 0.119 | **0.119** | 0.114 | **0.114** |
| - | 46 | [4] | 0.111 | **0.111** | 0.113 | **0.113** |
| Max velocity after preferred acceleration distance | | [55] | 0.094 | **0.094** | 0.126 | **0.126** |
| - | 125 | [60] | 0.111 | **0.113** | 0.126 | **0.126** |

* [73] = 20 field sport athletes, [84] = 1 male sprinter with a PB of 10.80 s, [4] = 8 US National level sprinters, [19] = 1 male sprinters with a PB of 10.15 s, [45] = 28 male recreational athletes, [55] = 10 male sprinters with a mean PB of 10.91 s, [60] = 1984 200 m Olympic Champion.

**Table 2. Mean touchdown distances from various distance/steps within a sprint**.

| Stage of sprint | Source* | Touchdown distance** (cm) |
|---|---|---|
| Step 1 | [68] | -13 |
| Step 2 | [68] | -4 |
| Step 3 | [68] | +5 |
| 16 m | [45] | +25 |
| 50 m | [3] | +40 |

* [68] = 25 male sprinters with PBs ranging from 10.20 s to 11.80 s, [45] = 28 male recreational athletes, [3] = 14 male sprinters with a mean PB of 10.83 s.

** Negative values represent the CM ahead of the stance foot.

**Table 3. Key biomechanical differences in stance phase characteristics between acceleration and maximum velocity.**

| Variables | Acceleration | Maximum velocity |
|---|---|---|
| **Ground contact times** | Longer | Shorter |
| **Ground reaction forces** | Greater emphasis on horizontal | Greater emphasis on vertical |
| **Joint kinetics** | Greater emphasis on net concentric power generation (particularly at the ankle and knee) | Greater emphasis on net eccentric power dissipation (particularly at the ankle and knee) |

**Table 4. Sample strength training exercises which could be utilised for the development of acceleration and maximum velocity sprinting during different phases of a training year.**[10]

<table>
<tr><th colspan="2">Phase</th><th>Acceleration</th><th>Max. Velocity</th></tr>
<tr><td rowspan="4">Specificity ↑</td><td>Specialised Developmental</td><td>Resisted sprinting<br>Short hill sprints</td><td>Weighted vest sprints<br>Speed bounding</td></tr>
<tr><td rowspan="2">Specialised Preparatory</td><td>High load sled towing<br>Standing long jump<br>Med ball dive throws</td><td>Hurdle jumps<br>Depth/drop jumps<br>Overhead med ball throw</td></tr>
<tr><td colspan="2">Jerks<br>Barbell squat jumps<br>Explosive step-ups</td></tr>
<tr><td>General Preparatory</td><td colspan="2">Clean and Snatch<br>Lunge and split squat<br>Squat and Deadlift (and stiff-legged)</td></tr>
</table>

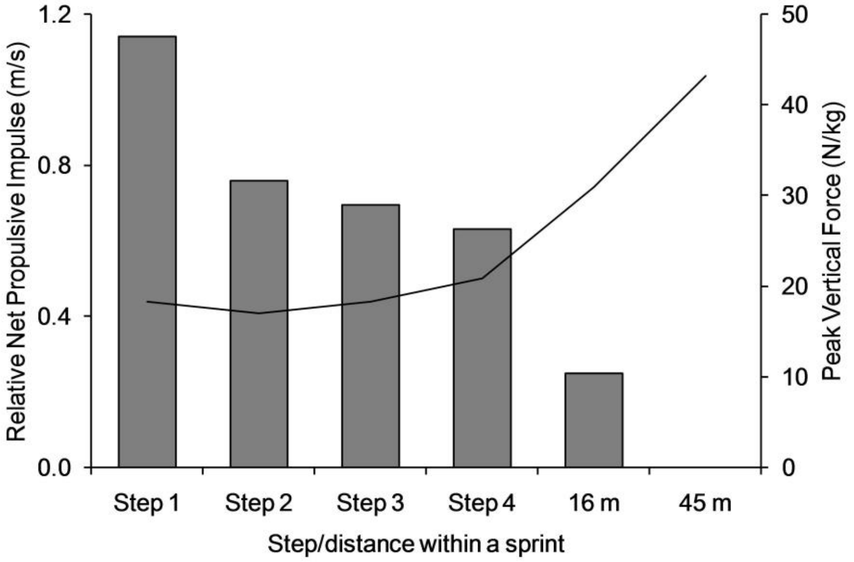


**Figure 1. Relative net horizontal propulsive impulse (bars) and peak vertical force production (line) during steps 1 to 4,[84] at the 16 m[47] and 45 m[70] marks within a sprint.**

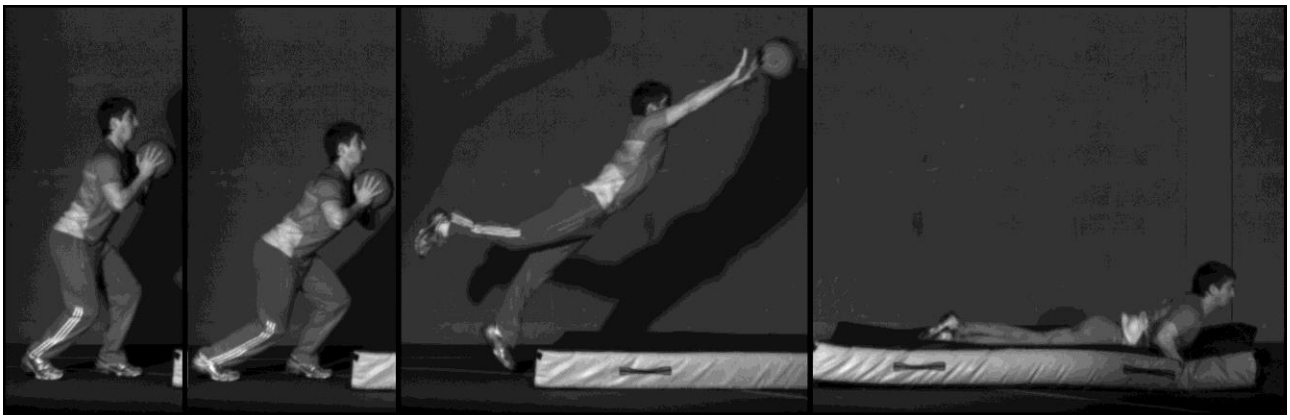

**Figure 2. Medicine ball dive throw.**

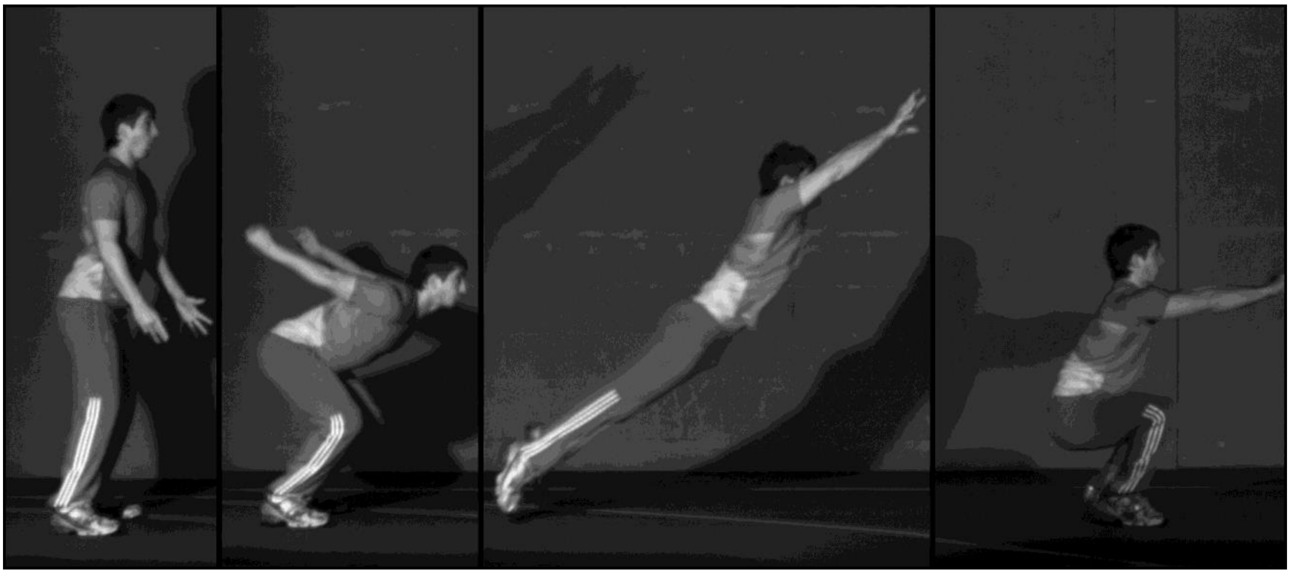

**Figure 3. Standing long jump.**

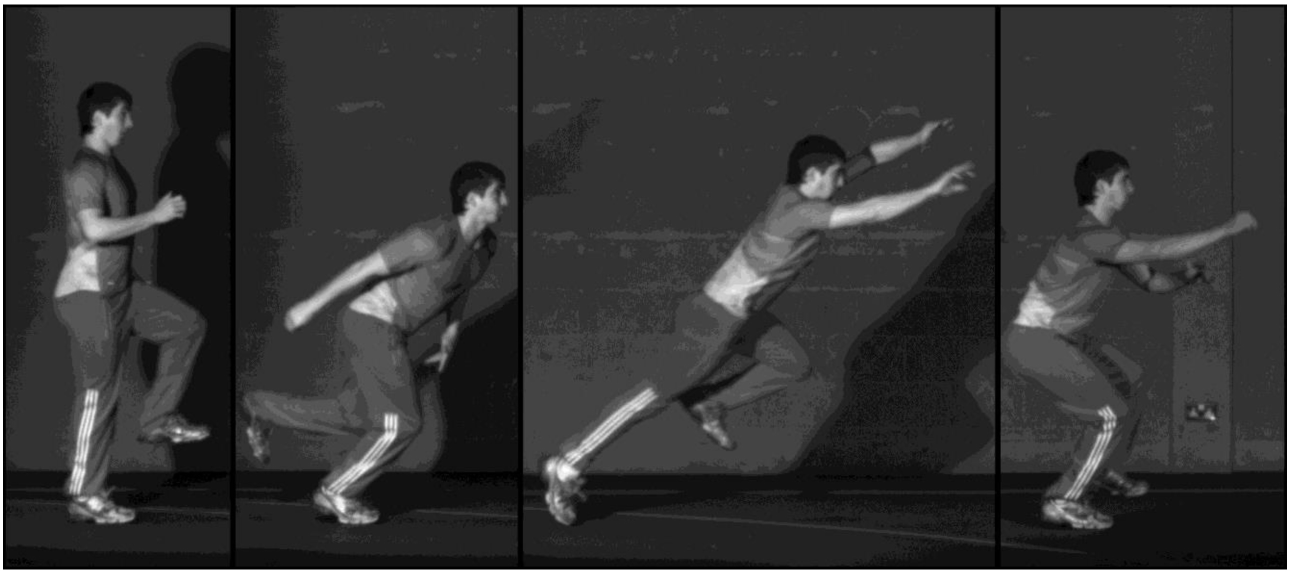

**Figure 4. Single leg standing long jump.**

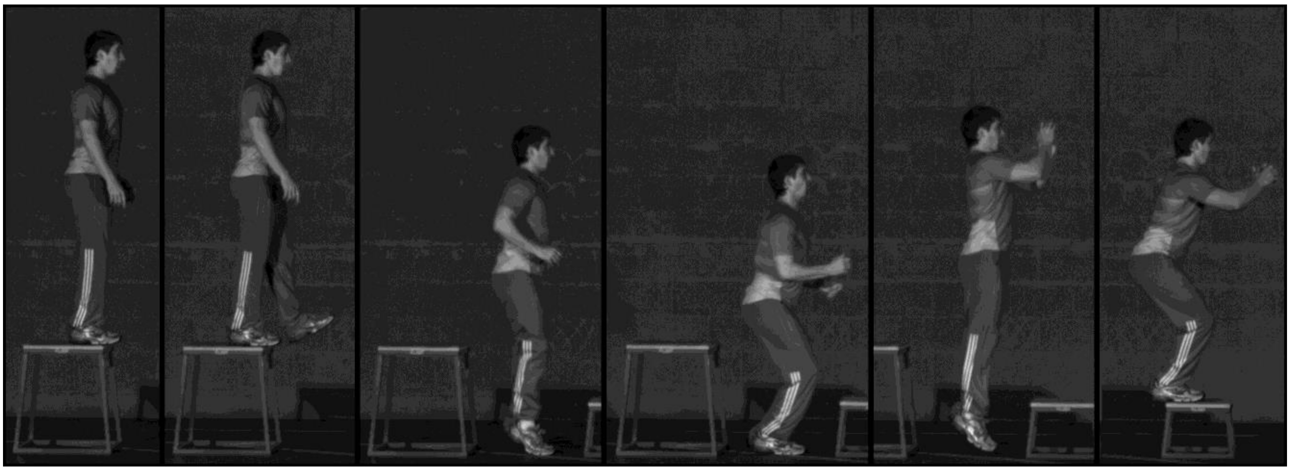

**Figure 5. Vertical depth/drop jumps.**

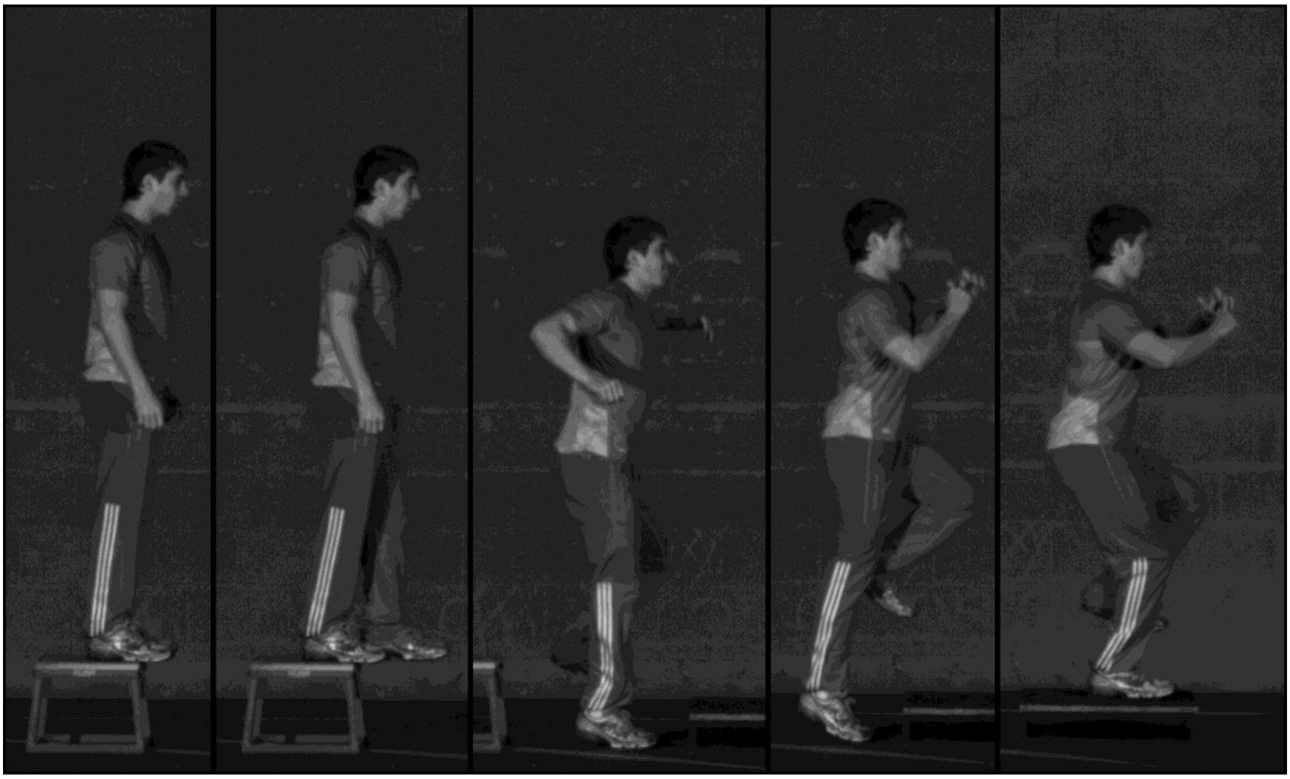

**Figure 6. Single leg vertical depth/drop jumps.**

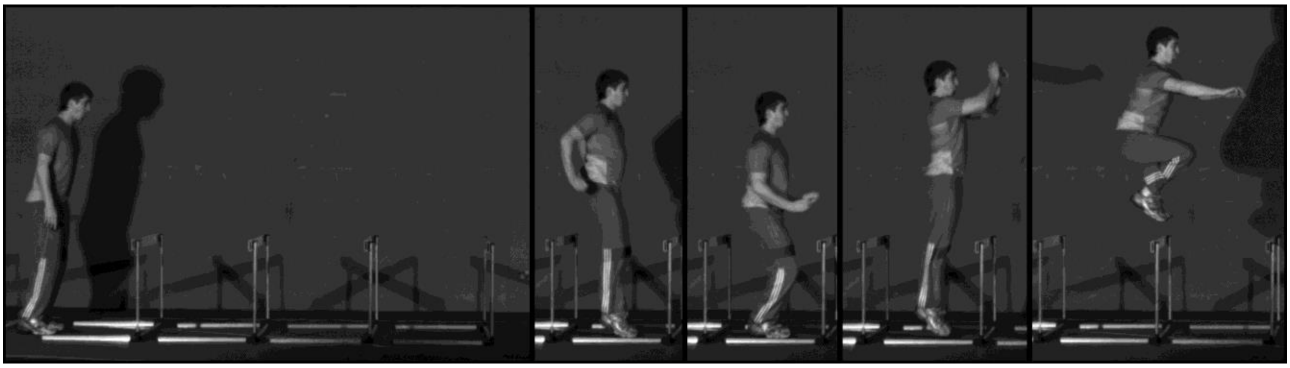

**Figure 7. Hurdle rebound jumps.**

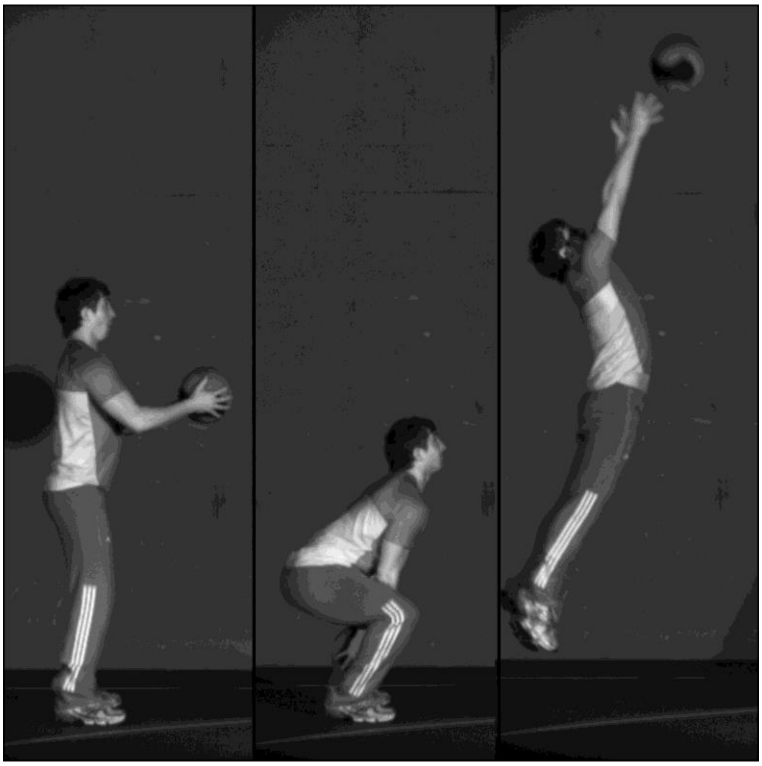

**Figure 8. Overhead medicine ball throw.**