Plyometric technical models: biomechanical principles

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OVERVIEW

The aim of this article is to provide coaches and developing coaches with a resource for understanding the key biomechanical principles involved in effective plyometric exercise. At present, technical models have been published for different plyometric exercises in various resources, but this can create confusion and the impression that each exercise requires a unique understanding. In contrast, this article will explain the key technical principles that a coach should be considering when developing their mental model of plyometric exercise training.

Introduction

The term plyometrics is used to describe a training method consisting of jumping, bounding and hopping exercises.[2,13,14,20] It is widely accepted that in order for an exercise to be considered a plyometric, it must utilise the stretch shortening cycle (SSC). The SSC is characterised by an eccentric action, an amortisation phase (where the muscle action transitions from eccentric to concentric), and an immediate concentric contraction.[1] The SSC enhances the ability of the neural and musculo-tendon system to produce maximal force in the shortest amount of time.[1] The occurrence of this muscle action during plyometric movements has contributed to plyometric exercise being frequently prescribed during training.

Schmidtbleicher[19] categorised SSC ability into either fast or slow expressions: a fast SSC action is characterised by small angular displacements in the hip, knee, and ankle joints (stiffness), with a ground contact time (GCT) that lasts between 100 and 250 ms; whereas a slow SSC action is characterised by a GCT in excess of 250 ms and greater angular joint displacement (compliance). However, it should be appreciated that these SSC capabilities live along a continuum and are not clearly distinct categories. For example, Lloyd, Oliver, Hughes, & Williams[11] reported that an intermediate SSC may be considered. They reported that submaximal hopping, measuring leg stiffness, reactive strength index and a countermovement jump are all independent qualities utilising a form of SSC with varying GCTs and mechanisms (see Figure 1 on page 14). Consequently, training exercises should be selected with the consideration of a GCT specific to the desired adaptation, the sporting scenario, and an intensity suited to the individual's current capabilities in order to reduce injury risk.

If effective and efficient fast-SSC exercises are to be utilised, it is important that the athlete's technical execution is developed. For example, as discussed later, effective fast SSC utilisation is reliant on the athlete

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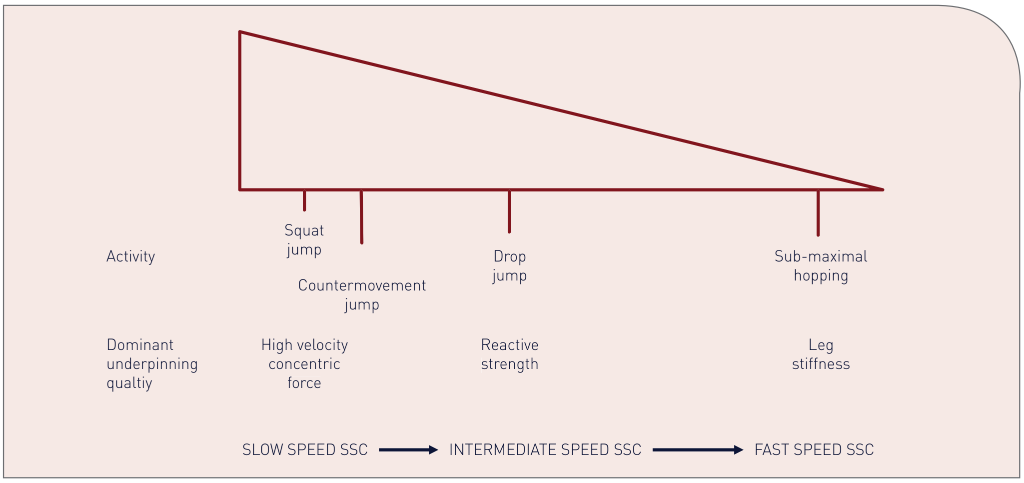

Figure 1. A visual representation of different SSC expressions. Adapted from [11]

producing effective pre-activation prior to ground contact and being able to control their centre of mass (COM) throughout flight and the amortisation phase.

Once an athlete has demonstrated effective kinematics, the coach may have more options when it comes to exercise selection. At this stage, it is imperative for the coach to understand that GCT and the associated SSC mechanisms are task-dependent outcomes, which meaning that the interaction between the loading induced by the task (exercise) and the athlete's capability determines the potential GCT. During the execution of all drills, an intent to get off the floor as quickly as possible should be encouraged even if a plyometric exercise is considered to be a 'slow SSC exercise' (due to desired jump height/distance and level of eccentric loading at ground contact).

If a repeated broad jump is being utilised with a desire to enhance slow SSC function, and the athlete's GCT is 'too fast', the athlete should be asked to jump higher/further to increase forces upon landing and increase the time required to generate force in the subsequent jump. The athlete should not simply be asked to produce a slower GCT. In addition, if an athlete is performing a 'fast SSC exercise' and their GCT is too slow, then if the coach is satisfied that the athlete is performing the exercise with maximal intention, the desired jump height or eccentric force upon ground contact (drop/fall height) should be lowered accordingly, in order to allow the athlete to produce enough force in the desired time frame.

Even with optimal exercise selection and appropriate intensity, there are a range of key biomechanical principles to which the coach must ensure the athlete adheres during exercise execution. These principles are required in order to allow optimal SSC utilisation and development, to minimise injury risk, and to increase transfer to athletic tasks. These principles remain the same for all plyometric exercises and their understanding can facilitate greater clarity of the technical models that should be understood to optimise the coaching and training process. The principles are presented in an order of importance, which may also provide coaches with clarity on the hierarchy of error detection and correction during coaching.

Biomechanical principles of technical execution

PRINCIPLE 1: FULL BODY PRE-ACTIVATION PRIOR TO GROUND CONTACT

During plyometric exercise, the body is expected to produce force in a highly time-constrained task. In order for this to happen, the body must be pre-activated and in a position suitable to allow sufficient force to meet the task outcome (see Figure 2 on page 15). In order to facilitate this force production within the task's time frame, pre-activation helps to ensure that cross-bridge formation has begun and that the muscular system is in a position to co-contract, create stiffness and stability at a joint and transfer energy into the tendon.[2,4,8,15]

Pre-activation is typically associated with the ankle, where it is expected that dorsi-flexion is produced prior to ground contact in order to place the ankle joint in an advantageous position to produce force and that the rest of the lower leg is actively prepared for collision with the ground.[7] However, due to the intensity levels in plyometric exercise and the need to transfer force into the

Figure 2 (left). Full body pre-activation prior to ground contact

Figure 3 (centre). Load distribution at ground contact

Figure 4 (right). Frontal plane knee alignment upon landing

ground and move the COM, it should also be expected that pre-activation is visible throughout the kinetic chain, via hip and knee and ankle flexion (task-dependent), shoulder extension and postural rigidity (Figure 2). Horita et al[7] reported that knee joint pre-activation was a key determinant of fast or slow take-off velocity during drop jumping while pre-activation at the ankle remained important, but did not differ between exercises.

The full body pre-activation and 'triple flexed' position is also important to allow force to be distributed across the hip, knee and ankle upon ground contact (Figure 3). It is common for some athletes to land in a 'quadriceps dominant' position, where little to no hip flexion and trunk lean is used and force is only being dealt with through the anterior chain, creating a more quadriceps dominant stress, a greater likelihood of knee valgus and injuries such as ACL injury.[23] The use of a triple flexed position encourages the force contribution from the posterior chain, namely the gluteal complex and the hamstrings in order to reduce stress on the knee (see the following section).

PRINCIPLE 2: FRONTAL PLANE KNEE ALIGNMENT UPON GROUND CONTACT

It is well reported that frontal plane knee alignment is paramount for injury prevention and optimal force transference.[6,16] During the high velocity and likely high intensity eccentric landing phase of plyometric exercises, it is imperative that the athlete is capable of controlling frontal plane knee movement (Figure 4). This ability should be assessed at the start of any plyometric training routine and an inability to control this variable should become the primary training adaptation for an inexperienced athlete.[16]

These positions may be assessed during various screening movements such as a jump and stick or the landing of a box jump potentially aided by the use of a 2D frontal plane projection angle.[22] Even if an initial assessment of this ability is deemed satisfactory, this should always be of primary concern as exercise intensity progresses. Although the coach may have a primary focus on the knee position, there should still be an appreciation of the relationship between the hip, knee and foot position. For example, knee valgus is also commonly associated with foot pronation and hip internal rotation.[17,23] Knee valgus and hip internal rotation are probably reduced if the athlete has produced an effective full body pre-activation position prior to ground contact; this allows the athlete to utilise their posterior chain, increasing gluteal and hamstring activity. This increased activity is associated with improved frontal plane knee control and reduced ACL stress via greater posterior pull on the tibia.[23]

PRINCIPLE 3: DESIRED LEVEL OF COMPLIANCE OR STIFFNESS DURING LANDING

During jump-based training and plyometric movements, skill development during the landing phase is an important training adaptation.[21] When the athlete is landing, the ability to be compliant upon ground contact and to dissipate force becomes the key to limiting excessive mechanical stress on connective tissues when desired. However, the athlete should develop skills to control the level of compliance required to dissipate force and thus to not land in a passive manner.[18] When the athlete is landing but not aiming to fully dissipate force (rebound activities), a greater level of joint and leg stiffness should be expressed (less ankle, knee and hip displacement). The level of stiffness expressed should vary according to the requirement of a slow SSC (in tasks requiring large/long jumps) or a fast SSC (tasks requiring moderate/low jump heights) for the subsequent jumping task (Figures 5b, 6b, 7b, 8b).

Figure 5a.
Un-weighting/pre-activation period of a CMJ

Full body pre-activation

Figure 6a.
Pre-activation position for a broad jump

Figure 5b.
Amortisation phase of a CMJ

Desired level of stiffness or compliance based upon the task

Ground contact time as fast as possible

Figure 6b.
Amortisation phase for a broad jump

Figure 5c.
Take-off position during a CMJ

Force contribution from all available sources

Centre of mass in line with direction of force vector

Figure 6c.
Take-off position for a broad jump

PRINCIPLE 4: INTENTION FOR GCT TO BE AS FAST AS POSSIBLE WITH SUFFICIENT COM DISPLACEMENT (REBOUND TASKS)

Although certain plyometric tasks may lend themselves to requiring a fast or a slow SSC naturally, it is important for the coach to appreciate the role of the task and the individual's capability in the expected GCT.[3,10] For example, if two athletes with different reactive strength capabilities both perform a hurdle jump over a 45cm hurdle – providing both athletes have an intention to produce maximal force in the correct direction – both will require a different GCT to clear the hurdle. The athlete with high reactive strength capabilities will show a shorter GCT with a greater amount of leg stiffness,[4] whereas the athlete with lower reactive strength capabilities will utilise a slower ground contact time with more limb compliance, which allows him/her more time to produce force to clear the required hurdle height.

If the hurdle height utilised was relative to the athlete's reactive capabilities and an intention for maximal force was maintained, the GCT between the athletes would be similar. If the desired adaptation in training was slow SSC enhancement (specific to the sport or individual weakness) and an athlete was performing a task where the coach felt the GCT was too fast, it is the task that should be adjusted via increased intensity, not the athlete's intention. However, during tasks with high COM fall heights and high levels of eccentric stress, it may be that the athlete needs to reduce their stiffness levels on ground contact to reduce the likelihood of Golgi Tendon Organ inhibition and ensure optimal force production.[10] This would likely be achieved by allowing greater ankle, knee and hip displacement during yielding (Figures 5b, 6b, 7b, 8b).

PRINCIPLE 5: CENTRE OF MASS IN LINE WITH THE VECTOR OF FORCE APPLICATION

In order to transfer force into the ground and move your COM, it is important that the athlete's COM is located above the direction of force application in order to ensure effective energy application. For example, if a horizontal dominant jump is utilised, effective take-off will be characterised by a forward lean of the trunk (moving the athlete's COM in front of their BOS) and applying force posteriorly, which is transferred through the trunk. A mis-alignment of the body's COM and BOS is likely to affect joint angles at either the hip or the knee, which will subsequently affect the SSC, as greater alignment of the vertical ground reaction force vector, relative to the joints (less joint flexion), reduces the movement arm of the ground reaction force and increases leg fast SSC capabilities (Figures 5c, 6c, 7c, 8c).[4,8]

PRINCIPLE 6: FORCE PRODUCTION CONTRIBUTION FROM ALL AVAILABLE SOURCES

During plyometric exercises, the whole body should be utilised to facilitate the displacement of the COM into the desired direction. The use of the arm swing is reported to contribute to counter-movement jump height via an increase in take-off velocity of 6-10%.[5,12] Therefore, the coach should encourage rapid shoulder flexion at the onset of concentric force production to aid propulsion. During the counter movement phase of single repetition jumps and the downward phase of flight in a series of rebound jumps, the opposite should be expected. The athlete should perform rapid shoulder extension to encourage the speed at which the COM lowers during single repetition jumps.

In the downward flight phase of multiple repetitions, the same movement should occur to ensure an early production of concentric force upon landing for the next subsequent jump. This enhances full body pre-activation and also ensures that the upper body is able to enhance the SSC speed by contributing to the displacement of body mass at the onset of ground contact. In contrast, if the shoulder is left in flexion, the arm swing is unable to contribute to the propulsive forces or causes a delay in the onset of maximal concentric force due to the shoulder still travelling through extension and pre-activating (Figures 5c, 6c, 7c, 8c).

Practical examples

COUNTERMOVEMENT JUMP AND BROAD JUMP

During countermovement jump performance, the task requires the athlete to create a vertical displacement of their COM as high as possible. In order to achieve this, the 'countermovement' portion of the task (an unweighting period before the eccentric breaking phase) should show full body pre-activation via triple flexion (flexion at the ankle, knee and hip) and a slight trunk lean (Figure 5a). Pre-activation should also be seen at the shoulder complex with rapid shoulder extension. This places the athlete into a pre-flexed position where the body is pre-activated and capable of the greatest force production. The position of the athlete's COM should be controlled via

> 'During plyometric exercises, the whole body should be utilised to facilitate the displacement of the COM into the desired direction'

Figure 7a.
Pre-activation during flight of a pogo hop

Full body pre-activation

Figure 8a.
Full body pre-activation during flight of a hurdle jump

Figure 7b.
Amortisation phase during a pogo hop

Desired level of stiffness or compliance based upon the task

Ground contact time as fast as possible

Figure 8b.
Amortisation phase during a hurdle jump

Figure 7c.
Take-off position during a pogo hop

Force contribution from all available sources

Centre of mass in line with direction of force vector

Figure 8c.
Take-off position during a hurdle jump

'Once an athlete has demonstrated effective kinematics, the coach may have more options when it comes to exercise selection'

both anterior-posterior and medial-lateral hip and trunk displacement to ensure that the COM remains directly above the BOS to ensure optimal transference of force through the kinetic chain (Figure 5c on page 16). From this position, maximal force should be produced as fast as possible via triple extension and shoulder flexion to create maximal jump height (Figure 5c).

During landing, the body should again be pre-activated to deal with the forces upon impact. If deceleration is desired (single repetition exercises), then force should be dissipated via compliant lower limb movement utilising eccentric muscle actions. If a rebound is desired upon landing, then the body needs to pre-activate in preparation to produce maximal concentric force upon ground contact, which again includes rapid shoulder extension and triple flexion during descent (prior to ground contact). It should also be remembered that frontal plane knee alignment should be maintained during all phases of the movement.

If a broad jump is performed, all of the key technical factors will remain the same – other than those that must adjust to the task demands. The uniqueness of a broad jump – compared to that of the countermovement jump – is that the task is to create both vertical and horizontal displacement of the COM. Therefore, the only things that should be expected to change are the relationship between the BOS and COM before the propulsion phase begins. In order for the COM displacement to take place vertically and horizontally, the COM must be in front of the BOS, creating a 'forward lean' position and a positive shin angle (Figure 6c on page 16). This allows force to be produced, transferred through the COM and the desired displacement to be created. If the broad jump is to be performed with multiple rebounding repetitions, then GCT should be expected to be longer as the BOS must be in front of the COM during landing to reduce the body's momentum (Figure 6b on page 16) and time must be allowed to ensure that the COM can 'overtake' the BOS and again reach the desired propulsive position (Figure 6c).

POGO HOP AND HURDLE JUMP

A pogo hop is an exercise likely to be utilised to develop the mechanisms that underpin a fast SSC. The task requires the athlete to produce multiple rebounds off the ground in a vertical motion with minimal GCT. This exercise is associated with low levels of intensity to ensure that GCT is kept short (Figure 7b). Subsequently, the exercise can be completed with minimal pre-activation or pre-activation more isolated to the ankle. However, the athlete should still be encouraged to utilise full body pre-activation (Figure 7a), where the knee, hip and shoulder contribute to the propulsion (Figure 7c), as this will ensure that skills are developed and can be transferred to exercises of higher intensities. As the task is again related to vertical displacement, the athlete's body position should ensure that his COM is located above his BOS.

Over time, the athlete may be progressed to a hurdle jump where the task now requires some horizontal displacement, but maintains a vertical emphasis. This may increase GCT in comparison to the pogo jump to ensure time to control the athletes COM (Figure 8b). Intensity will also have increased via the use of a hurdle, which can provide greater task demands due to the force needed for height of hurdle clearance and greater eccentric stress from the increased height of the COM before falling to the ground.

Conclusion

It is important for the S&C coach to understand the biomechanical principles of plyometric exercises. Although familiarisation with the technical model and nuances of each exercise is important, by following the explained principles, the S&C coach can have confidence that the athlete is performing safe and effective exercises. These principles should also be prioritised in the order presented and may assist the coach in diagnosing errors in technical execution.

AUTHORS' BIOGRAPHIES

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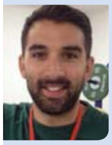

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References

1. Bobbert, M, Gerritsen, K, Litjens, M and Van Soest, A. Why is countermovement jump height greater than squat jump height? *Med Sci Sports Exerc*, 28:1402-1412. 1996.
2. Bobbert, M and Casius, L. Is the effect of a countermovement on jump height due to active state development. *Med Sci Sports Exerc*, 37(3): 440-446. 2005.
3. Chen, H, Hippenmeyer, S, Arber, S and Frank, E. Development of the monosynaptic stretch reflex circuit. *Curr Opin Neurobiol*, 13(1): 96-102. 2003.
4. Farley, C, Houdijk, H, Van Strien, C and Louie, M. Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. *J Appl Physiol*. 85(3):1044-1055. 1998.
5. Harman, E, Rosenstein, M, Frykman, P and Rosenstein, R. The effects of arms and countermovement on vertical jumping. *Med Sci Sports Exerc*, 22(6): 825-833. 1990.
6. Hewett, T, Myer, G, Ford, K, Heidt, R, Colosimo, A, McLean, S, Van den Bogert, A, Paterno, M and Succop, P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*, 33(4): 492-501. 2005.
7. Horita, T, Komi, P, Nicol, C and Kyröläinen, H. Interaction between pre-landing activities and stiffness regulation of the knee joint musculoskeletal system in the drop jump: implications to performance. *Eur J Appl Physiol*, 88(1-2): 76-84. 2002.
8. Kuitunen, S, Komi, P and Kyrolainen, H. Knee and ankle joint stiffness in sprint running. *Med Sci Sports Exerc* 34(1): 166-173. 2002.
9. Kyröläinen, H, Avela, J, McBride, J, Koskinen, S, Andersen, J, Sipilä, S, Takala, T and Komi, P. Effects of power training on mechanical efficiency in jumping. *Eur J Appl Physiol*, 91(2-3): 155-159. 2004
10. Leukel, C, Taube, W, Gruber, M, Hodapp, M and Gollhofer, A. Influence of falling height on the excitability of the soleus H-reflex during drop-jumps. *Acta Physiol*, 192(4): 569-576. 2008.
11. Lloyd, R, Oliver, J, Hughes, M and Williams, C. Specificity of test selection for the appropriate assessment of different measures of stretch-shortening cycle function in children. *J Sports Med Phys Fit*, 51(4): 595-602. 2011.
12. Luhtanen, P and Komi, P. Mechanical power and segmental contribution to force impulses in long jump take-off. *Eur J Appl Physiol Occup Physiol*, 41(4): 267-274. 1979.
13. Markovic, G and Mikulic, P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med*, 40(10): 859-895. 2010.
14. McBride, J, McCaulley, G and Cormie, P. Influence of preactivity and eccentric muscle activity on concentric performance during vertical jumping. *J Strength Cond Res*, 22(3): 750-757. 2008.
15. Moritani, T, Oddsson, L and Thorstensson, A. Activation patterns of the soleus and gastrocnemius muscles during different motor tasks. *J Electromyogr Kinesiol*, 1(2): 81-88. 1991.
16. Myer, G, Faigenbaum, A, Ford, K, Best, T, Bergeron, M and Hewett, T. When to initiate integrative neuromuscular training to reduce sports-related injuries in youth? *Current sports medicine reports*, 10(3): 155. 2011.
17. Powers, C. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *J Orthop Sports Phys Ther*, 33(11): 639-646. 2003.
18. Rozzi, S, Lephart, S, Gear, W and Fu, F. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *Am J Sports Med*, 27(3): 312-319. 1999.
19. Schmidtbleicher, D. Training for power events. In: *Strength and power in sport*. Vol 1. Komi P, ed. Oxford, England: Blackwell Scientific Publications, 1992. pp. 381-395.
20. Spurrs, R, Murphy, A and Watsford, M. The effect of plyometric training on distance running performance. *Eur J Appl Physiol*, 89(1): 1-7. 2003.
21. Sugimoto, D, Myer, G, Foss, K and Hewett, T. Specific exercise effects of preventive neuromuscular training intervention on anterior cruciate ligament injury risk reduction in young females: meta-analysis and subgroup analysis. *Br J Sports Med*, 49(5): 282-289. 2015.
22. Willson, J and Davis, I. Utility of the frontal plane projection angle in females with patellofemoral pain. *J Orthop Sports Phys Ther*, 38(10): 606-615. 2008.
23. Yu, B and Garrett, W. Mechanisms of non-contact ACL injuries. *Br J Sports Med*, 41 Suppl 1: i47-51. 2007.