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WHERE EVIDENCE MEETS PRACTICE

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The Track and Cross Country Journal is a refereed scientific journal published with the goal of advancing track and cross country knowledge through research and expertise. The Track and Cross Country Journal seeks to provide readers with up-to-date information comprising advances in all areas of track & field and cross country. Published articles include both detailed scientific manuscripts and "Coaches Notes" geared towards coaches, allowing for immediate application in the field. Care to be a contributor? *Contact us at info@tccjournal.org or phone 641-512-1736.*

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(641) 512-1736 | FAX (708) 209-3154
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WWW.TCCJOURNAL.ORG

Learning Progressions to Safely Teach the Pole Vault

James H. Bemiller, J.D. & Robin Hardin, Ph.D.

The University of Tennessee

ABSTRACT

The pole vault is an exciting and potentially dangerous sporting event for high school and college participants in the United States. One contributing factor for the potential danger and subsequent injuries is thought to be technique flaws which reduce the efficient transfer of energy from the approach run limiting the athlete's ability to penetrate safely into the landing area. Much discussion has taken place in the United States regarding the sufficient padding of the landing and surrounding areas and the mandatory use of helmets to increase the safety of the event. These risk reduction measures ignore the central issue of poor technical performance by the athlete resulting in uncontrolled attempts. The most effective method of reducing risks in the pole vault is to establish sound technique through the use of proper learning progressions for the beginner. The pole vault is safe and one of the best examples of overall athletic ability in sport when proper technique is learned.

Simplifying the concepts of pole vaulting technique allows for integration of sound biomechanical theory with practical coaching practices for the benefit of the beginning vaulter. Understanding the importance of proper learning progressions will result in safer and improved performance. The pole vault is a challenging athletic event which can be presented to athletes in a clear and understandable process. This pole vault progression discussion reinforces the fundamental theoretical concepts of safely learning the core concepts of the double pendulum action. The risk of the event is greatly reduced when athletes master the proper learning progressions before they attempt flexible pole vaulting. Skill development must be established through straight pole progressions to ensure safe and effective technique.

Learning Progressions to Safely Teach the Pole Vault
Executed properly the pole vault is one of the most dynamic and appealing events in sport. The complexity of the event can be daunting to the inexperienced athlete and coach. The pole vault is a double pendulum formed by the first pendulum of the pole rotating in the planting box toward and through the vertical plane, while the athletes' body constitutes the second pendulum swinging from the grip of the top hand on the pole. The energy to propel this athlete-pole system is generated by the

Figure 1: Full Vault Sequence

athlete during the approach and takeoff (Katsikas, Papaiakovou, Pilliandidis, & Kollias, 2003). Asking a young athlete to attempt a vault on a flexible pole without the proper learning progression increases the risk that the athlete will not have full control over her/his body or the pole. Without proper control of the double pendulum action the athlete will fail to effectively move the pole through the vertical or control the swing into the landing area resulting in the potential risk of injury.

The pole vault is ranked as one of the more dangerous sporting events for high school and college participants in the United States (Meuller & Cantu, 2007). The contributing factor for these injuries is thought to be technique flaws which reduce the efficient transfer of energy from the approach limiting the athlete's ability to penetrate safely into the landing area. Teaching inexperienced vaulters the proper progression of skills required for safe vaulting would likely reduce the risk of injury and increase performance (Rebella, Edwards, Greene, Husen, & Brousseau, 2008). Much discussion has taken place in the United States regarding the sufficiency of the landing area and the mandatory use of helmets at the scholastic level to increase the safety of the event. These measures can be valuable in reducing risk, but the most effective method of reducing risk in the pole vault is to establish sound technique through the use of proper learning progressions for the beginner. The pole vault is safe and one of the best examples of overall athletic ability in sport when proper technique is learned.

PROGRESSIVE STAGE LEARNING

Teaching the proper movements involved in pole vaulting is done safely and effectively by introducing the fundamental concepts of the event in successively related exercises to culminate in the full movement. This article integrates concepts of proper pole vault technique into practical recommendations for the coach working with beginning vaulters. The goal is to assist coaches to effectively train sound technique to enhance skill development and safety. A common complaint regarding the event is the reluctance to introduce beginners to the pole vault because of the coaches' lack of experience, knowledge, or "fear" of the event (Bemiller & Hardin 2010). The misconception must be dispelled that the pole vault is too technically complicated for coaches with no personal competitive experience in the event. Perhaps because of the amount of research done on the biomechanics of elite pole vault technique, with comparatively little peer reviewed publication of information regarding teaching proper learning progressions, coaches have resisted committing to an event with which they are not personally familiar (Kovacs, 2007). This discussion translates core concepts of proper pole vault mechanics into practical explanation to develop a safe learning progression for the event.

PROGRESSION OVERVIEW

The pole vault is one continuous action from the first steps of the approach run until the athlete lands safely in the pit (Petrov, 1985). Consider the complexity of full approach vaulting on the modern fiberglass pole. The young athlete must run at maximum controllable speed with a pole 3.5 to 5 meters in length, then drop the end of that pole into a sunken planting box at the end of the runway while preparing to jump off the ground and swing upside down on that bending and then straightening pole to clear the crossbar. This is a daunting task for a beginner, and should not be attempted until the athlete becomes proficient in short approach vaulting on non flexible (stiff) poles. The vault can be broken into the following progressive stages for instructional purposes.

1. Proper Grip and Posture – Simple takeoff progression to extend the pole overhead and take off from the ground while employing the correct grip and body position to move the pole safely to vertical and into the landing area.

2. Plant and Takeoff – Transitioning the pole from a carry position from a short approach to the extended takeoff position efficiently moving the pole through the vertical plane while generating pole speed toward the landing pit.

3. Swing Progression – Adding the second pendulum of the athlete swinging from the top hand and safely landing in the pit.

4. Short Approach and Beginning to Bend the Flexible Pole – Applying the preceding progressions to consistently generate pole and swing speed from a short approach run and transitioning onto a bending pole.

Coaches should consider the vault a sequential event, and the proper execution of each successive phase will have a positive influence on later phases (Petrov, 1985). Conversely, an athlete with technical flaws in the beginning phases of the event will have increased difficulty in executing later phases. Therefore, it is imperative that the athlete train in a proper learning progression before attempting flexible pole vaulting.

Athletes will be prepared to safely control the pole and their bodies when attempting actual full approach vaulting by beginning away from the vault runway to learn the proper sequence of movements. Proper fundamentals form the basis for continued improvement in the pole vault as they do in other athletic endeavors. Golfers must learn the proper grip and stance to be in position to succeed in executing a successful swing. Similar to a tumbling pass in gymnastics, the pole vault should be learned in a progressive sequence, with the supervision of a knowledgeable coach. The adherence to the mastery of proper fundamentals is imperative in the pole vault because of the speed of the vaulter, the characteristics of the flexible pole, and the need for the athletes to control their body and the pole while on the ground and in the air. The following discussion is an explanation of the beginning progressions of straight pole vaulting and transitioning onto a flexible pole. These progressions allow the beginner to safely ingrain proper technique while gaining experience and confidence.

BEGINNING PROGRESSION – GRIP, POSTURE, AND SIMPLE TAKEOFF

Vaulting, in its most basic form, is the concept of using the pole to assist the athlete in jumping off the ground. The fundamental concept of effectively moving the pole from the takeoff position through the vertical plane and into the landing pit is described as "pole speed." Effectively generating pole speed at takeoff transfers the horizontal kinetic energy generated by the vaulter in the approach to vertical potential energy through the pole. The pole must carry the vaulter to the crossbar and a safe landing in the pit (Butler, 2005). The most efficient way to begin is to practice extending the pole overhead and pushing the pole to vertical and beyond as the athlete jumps off the ground. (Descriptions are for a right handed vaulter jumping off the left foot.)

GRIP SELECTION FOR STRAIGHT POLE TAKEOFFS ON TURF OR TRACK

Start the basic progression on a level surface with a very low grip on the pole. To ascertain the proper grip height on a stiff, non bending pole, have the athlete stand with her/his feet shoulder width apart and place the pole vertically with the bottom plug on the ground between her/his feet. The athlete then reaches as high as possible and grabs the pole with her/his top (right) hand. The bottom (left) hand should also be placed above the athletes head. The distance of the grip between the hands on the pole should be approximately 15 to 25 centimeters (6"-10") apart. The width of the grip on non bending poles will be narrower than that used on flexible poles. While holding the top of the pole overhead with the correct spacing of the hands, both thumbs should point inward towards the body. When holding the pole overhead both hands should be under the pole, supporting the weight of the pole in anticipation of pushing or extending the arms and the top of the pole. Both arms must work together to extend the top of the pole above the vaulter's head.

JOG AND PUSH THE POLE OVERHEAD

Begin by carrying the pole overhead with both arms slightly flexed at the elbows. The top hand is above and slightly in front of the crown of the head, the bottom hand is held at approximately eye level with the left elbow close to the body and under the pole for support. The athlete can practice by jogging easily on a level surface and grounding the bottom end of the pole in the turf or track and extending the arms overhead while jumping forward and up to push the top of the pole up and over and then continue to jog upon landing.

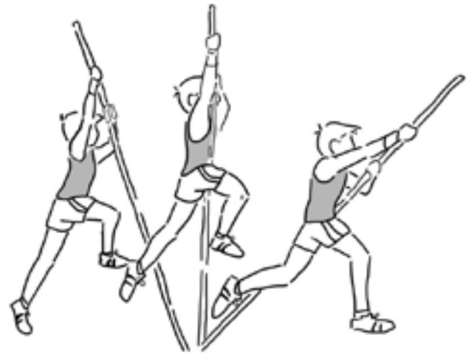


Figure 2: Jog and Push Drill

The right-handed athlete should use the right hand as their top grip and jump off their left foot and pass on the right side of the pole only after the pole passes through the vertical position. The tip of the pole should be carried above the grass until grounded, not slid along the surface. The arms should extend upward together in rhythm with the full body extension of the athlete through takeoff as the athlete rolls up and off the takeoff foot and actively leaves the ground. The right (lead) knee should be driven to a position parallel with the running surface to assist in the upward and forward momentum of the take off. The elbow of the bottom arm should move to the left of the pole as the athlete extends and pushes the pole smoothly up and over the vertical. Emphasis should be on full extension of the top arm, shoulders and chest while jumping off the ground. The pole should pass easily through the vertical and the athlete should remain upright and land on the right foot as they contact the ground and continue to jog.

Emphasize extending both arms upward above the head together in rhythm with the running cadence while jumping off the ground from the correct takeoff foot and pushing the top of the pole up and through the vertical position. The bottom arm will not extend fully after takeoff because of the low grip and stiff pole but should continue to assist with balance and moving the pole to vertical. Full extension of the top arm and body is critical to move the top of the pole through the vertical. As the top of the pole moves upward and forward, the vaulter's body will move upward into the pole and the chest and hips will meet the pole when it reaches the vertical position (Butler, 2005). The head should follow the extending arms and not be focused down toward the ground. Pulling with either arm should be eliminated. The vaulter may begin to gradually increase the grip height on the pole as she/he gains proficiency and confidence as long as she/he maintains proper posture and extension through takeoff and the pole continues to smoothly pass through the vertical.

POSTURE AND TAKEOFF POSITION

Posture is of paramount importance through the approach and takeoff. The athlete should maintain an erect posture with torso square to the direction of takeoff. By doing so the athlete is in a better position to extend fully through the takeoff and raise the top of the pole closer to the vertical position prior to leaving the ground. The higher the top of the pole as the athlete leaves the ground the easier it will be to move the pole to vertical. Emphasize the extension of the top arm and shoulder as the athlete rises off the extended takeoff leg. Breaking at the hips should be eliminated as this hinders preparation to extend the body and arms through takeoff. The takeoff foot should be directly underneath the extended top hand. Full body extension through all joints is imperative, except for the lead leg which is driven to a point at right angles to the trunk (Petrov, 1985). The position of the head should remain up with the eyes forward, allowing the body to extend and follow the top of the pole. Many beginning vaulters look toward the ground during the takeoff with their head and eyes, which should be discouraged.

PLANT AND TAKEOFF PROGRESSION:

Long Jump Runway and Sand Pit
Straight Pole Exercises

Once mastery of the simple takeoff progression on the flat surface is accomplished, move the vaulter to the long jump runway and sand pit. Use the same overhead carry, a short approach (1-3steps), and extension action described above now using the long jump runway into the sand pit before beginning to incorporate elements of proper pole carry and planting technique.

Gradually raise the grip and move the approach run back from 1 to 3 steps as proficiency on the long jump runway is demonstrated by the athlete being balanced and in control as they actively leave the ground and effectively move the top of the pole straight overhead and easily through the vertical. Continue to emphasize proper extension of the arms and the active motion of moving together with the top of the pole up and through the vertical such that the athlete lands and continues to jog out the back of the long jump pit. If the pole does not smoothly continue, stops, or stalls while attempting to move through the vertical the grip must be lowered until the proper approach speed and extension through takeoff is employed. The grip with which the vaulter can continue to extend and push the pole up and over the vertical will increase to between 30 to 60 centimeters (12”-24”) over the standing reach grip.

3-STEP APPROACH, PLANT ANDTAKEOFF INTO SAND PIT

The vaulter can practice proper grip, posture, and transitioning the pole from the carry position to the overhead extension of the top of the pole through takeoff from a 3-step approach. This is commonly referred to as “planting” the pole. Begin by taking an erect starting position with the right foot forward. The vaulter should hold the pole with the top hand (right) held above the right hip and close to the body. The left hand is positioned at the left center of the chest approximately 10 centimeters (4”) from the body. The elbows remain close to the trunk and the left elbow remains below the left hand. The pole should be supported by the left hand and both wrists are in a strong, cocked position (The biomechanical description would be to have both wrists in an actively flexed position). The pole should be balanced on the athlete’s skeletal system by the hands such that the posture of the athlete will not be detrimentally altered during the approach. This pole carry position establishes balance and approximates the natural arm position in sprinting.

From a short 4-step approach, the tip of the pole will begin slightly above eye level and will be lowered continuously throughout the approach. The lowering of the pole is controlled by the right hand moving upward close to and slightly behind the trunk. Begin with the top hand positioned above the athlete’s right hip and the bottom hand supporting the pole with the fingers of the bottom hand up as they curl around the pole. The left elbow should remain close to the body at the starting position and should be directed upward close to the body as the top of the pole is raised. The bottom hand and left elbow should not be cast forward during the raising of the pole but should be directed upward to compliment the erect posture of the athlete and continue the movement of the top of the pole toward the vertical plane. The bottom hand supports the pole and extends together with the top hand as the pole drops through the horizontal position parallel with the track. The planting action should be a smooth transition throughout the last three steps in synchronization with the rhythm of the athletes running approach. The arms should be synchronized with the legs similar to a basketball player extending his body and arms as they gather and jump to perform a layup or dunk. The top hand travels upward close to the body with both hands under the pole for support and control. Push or punch the pole upward for full extension of both arms and to aid in the jumping process. The upward action of the arms should begin three steps from takeoff as the second to last left step prepares to contact the ground and the tip of the pole has dropped below eye level. As the left foot (three steps before takeoff) contacts the ground the top arm controls the plant by shifting (flipping) the top hand up close to the right armpit. As the penultimate step (right) leaves the ground the top hand should be slightly above head height and slightly in front of the athlete's forehead. The last step (left) should be a full extension of both arms upward toward an imaginary crossbar which assists the athlete in a full body extension off the ground.

The vaulter continues to extend and drive the top of the pole to the vertical as the pole is grounded in the sand. The shoulders should extend and rotate upward as the pole rotates forward. As the athlete extends up and forward the chest and hips will meet the pole as the pole reaches the vertical. As the pole passes vertical the athlete will move past the right side of the pole, remaining in an extended vertical position. With the pole moving past vertical the athlete prepares to land on the right foot and finish by jogging through the sand pit.

Figure 3: 3-Step Plant Into Sand Pit

The body must remain tall and extended yet the muscles must remain tensed through takeoff.

The vaulter should keep the abdominal muscles tight during the approach to maintain proper posture and positively affect the transfer of energy through the extension of takeoff. Hanging loosely on the pole or pulling with the arms through takeoff must be eliminated. The vaulter also should be discouraged from breaking at the hips or swinging quickly past the pole before finishing a strong extended takeoff. The vaulter should be encouraged to actively control their body position and the movement of the pole through the vertical position. The vaulter can move to the pole vault runway when this progression is mastered.

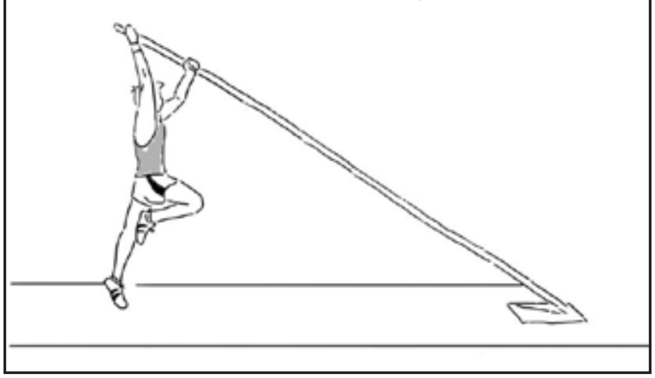
STRAIGHT POLE DRILLS ON THE POLE VAULT RUNWAY AND LANDING PIT

After the athlete has mastered the 3 step straight pole progression in the long jump pit by demonstrating a rhythmic and extended takeoff easily moving the pole through the vertical position they may move to the pole vault runway. Lengthen the approach to six steps with a stiff pole. Begin the approach with the athlete standing erect with the right foot slightly behind the left to establish balance and control of the vaulter-pole system. Rock back and then forward on the right foot to break inertia to begin the approach (Petrov, 1985). Continue to emphasize extending both hands while jumping off the ground and pushing the top of the pole up and over to land deep in the center of the landing pit while maintaining the forward speed of the pole. The vaulter should be encouraged to actively execute a tall aggressive takeoff with both arms fully extended above the head and a strong extension off the takeoff (left) foot while driving the right knee upward to facilitate pole speed and landing as deep in the landing area as possible. The planting action previously described will allow the vaulter to smoothly generate pole speed and move the top of the pole with the arms, shoulders and chest. The vaulter's torso will meet or bump the pole as the pole reaches vertical and both the pole and vaulter will travel through the vertical and into the center of the pit. After the pole has past the vertical and the athlete begins to descend to the landing pit they should lift their feet to land safely on their back and avoid turning their ankles or knees in the soft surface.

POSITION AT TAKEOFF

The takeoff foot (left) should leave the ground from a point directly underneath the fully extended top hand simultaneously with the pole tip striking the back of the planting box, or slightly before the pole strikes the back of the box. The fundamental concept is that the athlete should have the opportunity to complete the extension of the plant and have space to fully extend the entire body as much as possible and be free to execute an aggressive takeoff without resistance from the early grounding of the pole in the back of the box. With the takeoff foot placement directly below the top hand, the vaulter can extend the pole higher and closer to vertical as she/he leaves the ground. This foot placement gives the athlete the best opportunity to transfer energy from the approach to the pole (McGinnis, 1997). Do not allow the beginning athlete to deviate significantly from the proper takeoff point. Taking off more than 10 centimeters (4") inside (closer to the landing pit) or five centimeters (2") outside (farther from the landing pit) the correct point directly below the top hand will diminish the vaulters's posture and rhythm to aggressively transfer energy into the pole, making it more difficult to generate pole speed and land safely in the pit. Taking off with the left foot directly beneath the top hand maximizes the angle between the pole and runway at takeoff and is the most efficient position to move the pole to vertical. The vaulter should be moving onto the toe of her/his takeoff foot before the pole contacts the back of the planting box and the vaulter's body should be extended and taut through the arms, shoulder girdle and core to minimize energy loss through takeoff. Full extension through the takeoff is critical to transfer the energy of the approach so the vaulter may quickly and efficiently execute the succeeding stages of the vault. Continue to extend and move the top of the pole, stretching and moving upward and forward as the vaulter pushes the pole toward the vertical.

Figure 4: Take Off Position



Beginners must resist the instinct to pull into the pole or bring the pole closer to the body through takeoff. Pulling the pole toward the body and the failure to extend through the takeoff negatively effects pole speed and rotation to the vertical and impedes the athlete's ability to develop a dynamic takeoff and swing. Full extension of the plant and takeoff is critical to facilitate dynamic execution of the latter stages of the swing and clearance.

SWING PROGRESSION

The vaulter should execute the same straight pole six stride approach and aggressive takeoff previously described, but instead of landing in a seated position, she/he can swing or whip her/his takeoff leg (trail leg) aggressively to catch up with the right leg (lead leg). Then with both legs swinging and extending together, swing and extend the hips past the top hand toward the top of the pole, the vaulter can land on her/his back in the center of the landing area.

Figure 5: 6-Step Straight Pole Plant and Swing

The swing is facilitated through the shoulders. As the legs and hips aggressively swing up, the shoulders rotate under the hips becoming the rotation axis of the swing (Petrov, 2003). Focus should be on vaulting for horizontal depth utilizing the full rotation of the pole through vertical and safely into the center of the landing area. The vaulter can progress to landing in the pit on her/his left side, next to the pole, with her/his right hip touching the top hand and both legs extending together toward the back of the pit parallel to the pole. Initiate the turn after the pole has passed through the vertical and is falling toward the pit.

The grip on the pole can gradually be increased as long as the vaulter has sufficient pole speed through the vertical plane to swing and land safely in the pit. The vaulter should land in the pit next to the pole with their top hand closer to their chin as technique improves and she/he swings more aggressively. The next step in the improvement of the swing is for the vaulter to continue the swing and finally pull with the top hand past the chin while turning the right hip into the top of the pole. The vaulter should land on the pit on her/his chest stomach, and thighs with body extended parallel beside the pole with the right hip touching the top of the pole or beyond.

The concept of continuous movement from beginning of the approach to landing should be foremost in the mind of the coach and vaulter while executing the takeoff and swing progressions (Petrov, 2003). The vaulter should execute the takeoff and swing in an active and aggressive manner to maximize the energy potential of the vault to lift the center of gravity as high as possible. The actions of the vaulter must be continuous through the approach, transition of the pole through the plant and completion of the fully extended takeoff, and the execution of the swinging action. Both ends of the pole should be in constant motion. The bottom tip of the pole should be gradually lowered throughout the approach and transition through the takeoff until dropping into the center of the plant box and grounding against the back of the box. Conversely, the top end of the pole, controlled by the right hand of the vaulter, continually balances and raises the top of the pole at the same time the tip actively drops. The result is a fluid and balanced pole drop and transition into the extended takeoff position. The continuous action of the dropping pole results in increased momentum and pole speed through the takeoff. The athlete should never hold or stop the momentum of the pole drop or extension through the top of the pole through takeoff.

The pole is not lowered by dropping the left hand or casting the left hand toward the planting box. Box hands should extend upward supporting the pole. At no time should the vaulter wait or hang during the takeoff before continuing through the swing phase to the top of the pole. Excessive breaking at the waist or tucking of the knees while swinging will also impede the smooth continuation of swinging the center of gravity to the top of the pole. Pole speed will diminish and the athlete will have difficulty raising the top grip significantly to effectively use a bending pole if the takeoff and swing action is not continuous.

From this 6 stride straight pole action beginners can progress to the act of vaulting low crossbars by completing the turn into the pole and presenting their stomach to a low crossbar as they swing then turn. The crossbar should be placed at 80-110 cm (32”-44”) depth behind the back edge of the planting box to encourage pole speed and active penetration safely into the landing area. The vaulter should complete the vault by landing on his back in the middle of the landing pad. The athlete must continue to show proficiency in proper takeoff mechanics and pole speed to consistently land safely in the landing pit.

SHORT APPROACH PROGRESSION AND BEGINNING POLE BENDING

Straight Pole Takeoff with Longer Approach

Both coach and athlete must understand the critical importance of mastering straight pole technique. The fundamental concepts of effective preparation for takeoff and pole speed are the same with both the straight and flexible pole. As proficiency of the athlete’s takeoff and the speed of their approach increases, the vaulter should be capable of gripping 60 centimeters (24”) or higher above their standing grip and clearing crossbars within 30 centimeters (12”) of her/his handhold with a straight pole and six-step approach while landing consistently in the center of the landing area. Only when the previously described straight pole progressions are successfully mastered should the vaulter move on to attempting the use of longer approaches and be capable of bending a flexible pole with progressively higher grip heights.

Progression to flexible poles begins by increasing the length of the approach run to 10 steps with a non bending pole to acclimate the vaulter to faster approach speeds in preparation to begin bending the pole. The increase in approach speed will allow a corresponding gradual increase in grip height while straight pole vaulting with sufficient pole speed to land safely in the pit.

The vaulter is ready to begin bending the pole when proficiency from the 10-step approach is shown and the vaulter can consistently grip approximately 90 centimeters (36”) above his standing grip while executing an extended, aggressive takeoff, full swing and turn into the pole with a safe landing (Johnson, 2009).

BEGINNING BENDING OF THE FIBERGLASS POLE

The progression to using a bending pole should start by choosing a pole that is approximately 60 centimeters longer than the vaulter’s consistently successful non bending grip (12’-13’ length poles) and with a flex weight of at least the vaulter’s body weight. The vaulter should use a 10-step approach with the same top grip used to effectively straight pole vault. The width of the grip as measured between the thumbs and should be widened to approximately 50 centimeters (18”) or the width between the hands hanging naturally along the outside of the vaulter’s thighs. Instruct the athlete to fully and aggressively extend both arms through the takeoff, moving the top of the pole toward an imaginary crossbar five meters high (16’4.5”). Proper pressure with the arms and body position is an important factor in bending the pole.

The pole should begin to gradually bend away from the vaulter as they become accustomed to applying pressure with both hands through the top of the pole. The top arm must be fully extended through the shoulder, elbow and wrist joints, and apply strong pressure to the top of the pole upwards through the hands. The top arm should remain strong throughout the takeoff and not be allowed to drag significantly behind the head of the vaulter. The bottom arm should aggressively direct the top of the pole above the vaulter's forehead and may bend at the elbow approximately 90 degrees. The bottom hand should be under the pole with the knuckles facing upward. As the grip increases the extension of the bottom arm will increase. The bottom arm is very

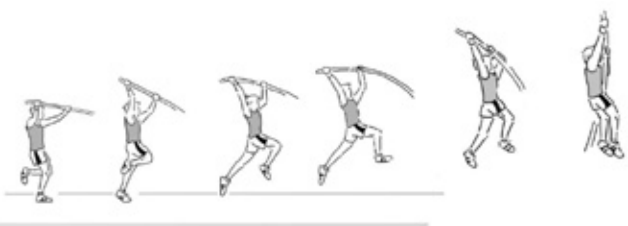


Figure 6: Flexible Pole Plant and Take-Off Drill

important in initiating the bend of the pole and should be actively engaged and extend above the vaulters' head through the takeoff. Both arms and shoulders elastically push and extend as they stretch above the vaulter's head.

The vaulter should keep her/his shoulders, core, and hips in a tensioned state and aggressively extend through the takeoff upward toward the crossbar and the back of the landing pit. The vaulter should drive the entire body upward through the direction of the hands while also keeping the head and eyes focused upward. The vaulter cannot merely relax his body and hang on the pole. Gymnastics coaches describe this tensioned state as the difference between a "taut" and "loose" body. Remaining taut, by pre-tensing the muscles throughout the takeoff and swing, transfers momentum from the approach run and planting action. This momentum is lost if the vaulter goes "loose," and it becomes difficult for the vaulter to control her/his body and the pole and penetrate safely into the pit.

The bending of the pole allows the vaulter to progressively grip higher but does not significantly change the vaulter's basic technique described in the previous straight pole exercise progressions. Vaulters and coaches must also understand that modern vaulting poles are manufactured to bend consistently in one direction; therefore the pole should be gripped to be in position to bend away from the athlete toward the landing pit, and slightly to the left, as the vaulter leaves the ground.

The goal is the same as the vaulter moves to gradually higher grips and bending poles, that is to execute a fully extended takeoff, moving the top of the pole easily past the vertical, and swinging the trail leg aggressively to facilitate rotation through the shoulders and swing to the top of the pole. The flexible pole will reduce the force of impact to the athlete at takeoff and decrease the effective length of the pole as it bends while rotating in the plant box, allowing the athlete to grip higher. The accessibility of higher grip heights and the elastic properties of the pole make sound technique imperative so that the athlete can control the pole and their bodies and land consistently in the landing area.

The length of the approach can be gradually increased as the pole begins to bend and the vaulter shows proficiency and confidence in performing the previously described progressions. A typical short approach of 10 to 14 steps will give the vaulter sufficient approach speed to consistently bend the pole. Begin using the same grip as from 10 steps and exerting pressure upward and forward from both arms with solid body extension through takeoff. The pole will begin to bend away from the vaulter as she/he becomes more aggressive and effective in the planting action.

The emphasis for the vaulter is the same as on an unbending pole – complete a fully extended takeoff generating pole speed toward the crossbar and the back of the landing area. Immediately after completing a fully executed takeoff the vaulter should continuously swing aggressively through the shoulders toward the top of the pole then extend the legs upward together while turning the right hip into the top hand and the top of the pole. The vaulter and pole work together to move the pole safely through vertical as the vaulter extends through the takeoff and swings with the pole to create momentum to safely land in the center of the landing area. The vaulter should never release the pole until she/he is sure of her/his orientation and a safe landing in the pit.

COMMON MISTAKES AND CORRECTIONS

Attention should be given to eliminating the common mistakes by beginners which detract from performing sound technique. In many instances, proper vaulting technique may conflict with the natural instincts of the beginning athlete. The following common mistakes should be corrected before they become habits which impede the technical progress of the athlete.

Poor Posture – Failure to keep an erect posture may be the product of an inexperienced vaulter trying to increase her/his speed on the runway by leaning forward and breaking at the hips or over striding. Poor posture may also be the product of an unbalanced transitioning of the pole from the carry to the plant and takeoff position. Maintaining erect posture should be emphasized to maximize the potential energy at takeoff by maintaining the vaulter's center of gravity as high as possible through the takeoff.

Head Down – Many beginning vaulters have a tendency to focus down at the runway and planting box. This may be a natural reaction to see the pole as it is planted in the box however; this position destroys proper posture and limits the transfer of energy through the hands and the top of the pole. The vaulter should be instructed to drop the tip of the pole into the middle of the planting box. As the vaulter extends through the takeoff, the pole will ground in the back of the box. The head and eyes should be focused up as the vaulter fully extends the entire body through the takeoff.

Inside Takeoff – Beginners should be discouraged from taking off inside the optimum position directly under the extended top hand. The novice may instinctually feel safer as she/he takes off closer to the landing pit but this is a destructive mistake. Taking off "under" has a compounding negative effect of destroying the vaulter's posture, limiting her/his ability to effectively extend through the takeoff as well as limiting the ability to swing. These negative implications ultimately limit the ability to effectively move the pole to vertical and the potential to improve the grip height on the pole.

Incomplete or Offset Plant – Full extension at takeoff should always be expected. The vaulter will usually drift to the right (right arm/top arm) or lack pole speed if she/he fails to fully extend the arms and body at takeoff. Fully extend through the takeoff, preferably immediately prior to the pole grounding in the back of the box to maximize pole speed and control the pole moving into the landing pit through the vertical plane. Vaulting on a flexible pole should not occur until the athlete can execute a balanced, extended takeoff.

Pulling – There is a natural tendency to pull the pole closer to the body as a falsely perceived sense of security. Pulling destroys pole speed, effectively stopping rotation of the pole to vertical. The vaulter should be encouraged to push and swing with the pole safely into the landing pit. Pulling during the takeoff should be eliminated.

Blocking with the Left Arm – Many vaulters try to create bend in the pole by forcing or locking the left arm out in front of the face during takeoff. This blocking action limits the full extension up of the arms and chest up and forward through takeoff and has a negative effect on pole speed and the vaulter's ability to swing. A grip that is too wide may also contribute to this problem; therefore the grip width should be closely monitored.

Both arms should extend fully with the top arm and shoulder next to the vaulter's right ear and the bottom arm also extended fully above the vaulter's head. The bottom hand will extend above the forehead through takeoff. Full extension of both arms through the takeoff is the best method of transferring the energy of the athlete's approach and takeoff to move the pole and allow the vaulter to swing to the top of the pole. After the takeoff the bottom arm may bend to a ninety degree angle to allow the chest to continue to penetrate forward and the pole speed to continue.

Not Landing in the Middle of the Landing Area - Adjustments must be made immediately if the athlete does not land in the middle of the landing area in control of their body and the pole. If the athlete does not leave the ground at the correct takeoff point adjust the approach and running mechanics accordingly as a faulty takeoff point may cause the athlete to lose momentum and control of the pole and their body in flight. If pole speed is insufficient to carry the athlete safely into the pit, lower the grip until proper pole speed and control is demonstrated. Excessive pole speed allowing excessive pole bend and penetration should be corrected by gradually raising the grip or flex weight of the pole. The athlete should always hold onto the pole for support and not release the pole until they are in control and safely in the landing area.

Casting the Pole to the Front- As the athlete prepares to plant the pole they may have a tendency to cast or push the pole forward rather than upward. Casting the bottom arm out away from the body diminishes the upright running posture of the athlete and causes the athlete to lose control of the pole through the takeoff. As the pole drops through the horizontal plane keep the pole balanced upon the athletes body by actively raising the top hand off and behind the right hip (freeing the hip) as the bottom hand remains close to the athletes torso and equally balanced to foster upright posture and a strong position to extend through the takeoff.

Vaulting toward the Crossbar- Many young athletes become fixated on swinging toward the crossbar prematurely. If the athlete is fixated on swinging toward the crossbar the pole does not move to vertical and instead she/he swings past the pole resulting in poor penetration into the pit and loss of body control in the air. The athlete should instead focus on creating pole speed and swing speed to move the pole to vertical and swing and extend in synchronization with the unbending pole to land safely in the landing area. The vaulter must redirect the horizontal momentum of the approach and takeoff to vertical momentum by swinging together with the unbending of the pole. The athlete should work with the pole to move the pole to vertical and swing past the top of the pole not toward the crossbar.

Inactivity/Hanging- Many beginners become inactive after the pole is grounded in the planting box. They may have the misconception that their work is complete and they only have to hang on for the ride, or they may have been out of position through the plant and takeoff such that they cannot actively control the in-air phase of the event. The instructor must emphasize that at no time should the athlete by passive or feel out of control of themselves or the pole. The movements should be continuous with no hesitations or breaks in momentum.

Releasing the Pole Prematurely- Serious injuries occur when athletes do not have sufficient pole speed to travel safely into the landing area and effectively stall out over the planting box and they choose to let go of the pole. Releasing the pole in this position exposes the athlete to great risk of injury from an uncontrolled fall. The athlete should be instructed to never release the pole until they are safely over the landing area. If the athlete is unsure of their orientation or position during any attempt they should hold onto the pole as support and swing to the ground or landing area in a controlled manner.

CONCLUSION

Simplifying the concepts of pole vaulting technique allows for integration of sound biomechanical theory with practical coaching practices for the benefit of the beginning vaulter. Understanding the importance of proper learning progressions will result in safer and improved performance. The pole vault is a challenging and exciting event which can be presented to athletes in a simple and understandable process. This pole vault progression discussion reinforces the core theoretical concepts of reacting positively to the takeoff and pushing the top of the pole to vertical while swinging past the top of the pole. The risk of the event is greatly reduced when athletes master the proper learning progressions before they attempt flexible pole vaulting. Skill development must be established through these straight pole progressions to ensure safe and effective technique.

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PREVENTING OVERUSE INJURIES IN RUNNING:
A PERSPECTIVE BASED ON TISSUE DAMAGE, REPAIR, AND ADAPTATION

W. Brent Edwards Ph.D. & Timothy R. Derrick Ph.D.

Department of Kinesiology and Nutrition, University of Illinois at Chicago

Department of Kinesiology, Iowa State University

ABSTRACT

Overuse injuries in running are injuries resulting from the mechanical fatigue of biological tissue. Repetitive loading will, over time, lead to the formation of tissue damage. Without adequate rest and repair, continued loading will cause damage accumulation that eventually may lead to injury. By adopting training patterns that allow for tissue repair, and encourage tissue adaptation, coaches may be able to avoid, or at least reduce, the occurrence of overuse injury in their athletes. In this review, we: 1) provide a brief overview of the mechanical fatigue process of biological tissue, and 2) discuss training patterns to allow adequate time for repair and exploit adaptation. The information presented suggests that the occurrence of overuse injury can be reduced by adopting some sensible training strategies during the first few weeks of a new running regimen.

INTRODUCTION

Performance enhancement of the team and individual runner remains the primary goal of a track and cross-country coach. Intimately linked to this goal is a coach's ability to keep their athletes healthy and free from injury. This can be a difficult task – runners sustain injuries at an alarming rate, especially during the first few weeks of a new training regimen. Although some of these injuries can be considered acute injuries (i.e., ankle sprain, muscle strain, spontaneous bone fracture), the large preponderance of running injuries are due to overuse (i.e., plantar fasciitis, Achilles tendonitis, patellofemoral pain, iliotibial band syndrome, stress fracture). It is estimated that 26% to 65% of runners, both recreational and competitive, will sustain some form of overuse injury during any given year (Caspersen et al., 1984; Lysholm & Wiklander, 1987; Macera et al., 1989; Marti, Vader, Minder & Abelin, 1988).

It is often said that overuse injury has a diverse and multifactorial etiology (Hreljac, 2005; Rolf, 1995; van Mechelen, 1992). This is true only when overuse injury is defined at the systems, or whole-body, level. Overuse injury is ultimately a biomechanical event that manifests at the tissue level, and is thus more easily defined at the tissue level. Overuse injury is an injury resulting from the mechanical fatigue of biological tissue. Here, fatigue refers to structural damage resulting from the application of repeated stresses or strains (stress is a measure force intensity defined as the force per unit area of a structure; strain is a normalized measure of structural deformation created by stress). Repetitive loading, such as that experienced during walking and running, will over time lead to the formation of microdamage. Without adequate rest and repair, continued loading will cause damage accumulation that eventually may lead to failure (i.e., injury). Any risk factor, whether it is intrinsic or extrinsic to the runner, will contribute to overuse injury through this process.

By and large overuse injuries take place when running intensity or running volume are increased too rapidly (Hreljac, 2005; van Mechelen, 1992). In this instance the tissue experiences cumulative stress beyond that which it is habitually accustomed to, and the tissue's natural defense mechanisms of repair and adaptation become overwhelmed. By adopting training patterns that allow for repair, and exploit adaptation, coaches may be able to avoid, or at least reduce, the occurrence of overuse injury in their athletes. The purposes of this review are to: 1) provide a brief overview of the mechanical fatigue process of biological tissue, and 2) suggest training patterns that allow adequate time for repair and encourage adaptation.

MECHANICAL FATIGUE

The fatigue life of a material is defined as the number of repetitive loading cycles a material may endure before complete failure occurs. The fatigue life of any material is heavily dependent on the resulting stress from the applied mechanical load. This type of fatigue behavior is often described using a stress-life plot, or S-N curve. An S-N curve characterizes the damage evolution, damage accumulation, and failure processes of a material into a single, empirical relationship (Suresh, 1998). Figure 1 illustrates a theoretical S-N curve of a biological tissue with stress, S, on the y-axis and the number of loading cycles to failure, N, on the x-axis. The slope of the S-N curve indicates that small changes in stress can result in large changes in the number of cycles to failure.

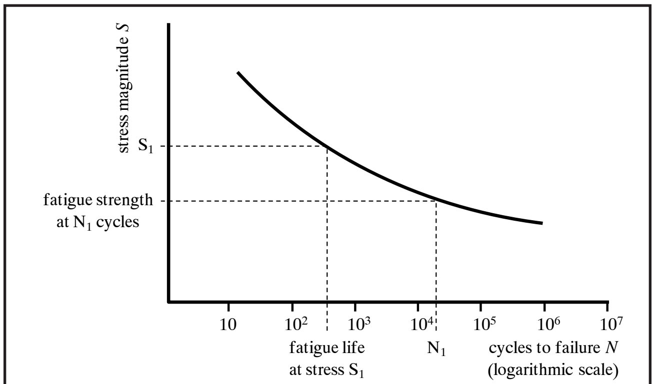

Figure 1.

It would be highly difficult, if not impossible, to characterize the fatigue behavior of biological tissue in vivo. Consequently, what we currently know about the fatigue behavior of biological tissue comes from ex vivo testing of cadaveric specimens (Carter and Caler, 1985; Carter et al., 1981; Schechtman and Bader, 1997; Weightman, 1976; Weightman et al., 1978; Wren et al., 2003). The disadvantage of this approach is that it does not allow for the inclusion of concurrent repair and adaptation that are known to occur with mechanical loading. Repair and adaptation may increase the fatigue life associated with a particular stress. Therefore, ex vivo data provide a conservative estimate of a tissue's fatigue behavior under various loading scenarios.

Some equations defining the relationship between the number of cycles to failure and stress for various biological tissues are presented in Table 1. Also included in this table, are ranges of typical stresses experienced by biological tissue during running, as well as the percent change in fatigue life associated with a 10% change in stress magnitude. In general it can be seen that for the magnitudes of stresses relevant to running, a 10% change in stress leads to a corresponding 100% change, or more, in the number of cycles to failure. Thus, any mechanism that can be adopted by the runner to reduce the stress experienced by tissue during running may reduce the prevalence of overuse injury. Such mechanisms may include decreasing stride length (Edwards et al., 2009) or running speed (Edwards et al., 2010).

HOW MUCH IS TOO MUCH?

When increases in running intensity or running volume are too large the rate of damage accumulation will outweigh the rate of tissue repair and an injury will occur. Here it is important to note, based on the non-linear nature of fatigue behavior, that the cumulative stress, or damage, provided by a percent increase in running intensity is not the same as that provided by a percent increase in running volume.

Whereas the risk for overuse injury would increase proportionately with running volume, the risk would increase rapidly and in a non-linear fashion with increases in running intensity.

This concept can be illustrated with an example of the second metatarsal, a bone predisposed to stress fracture due to the large bending loads it receives during the push-off phase of running. Using a modeling technique called the finite element method, we approximated the relationship between running intensity (speed) and second metatarsal stress. (Figure 2)

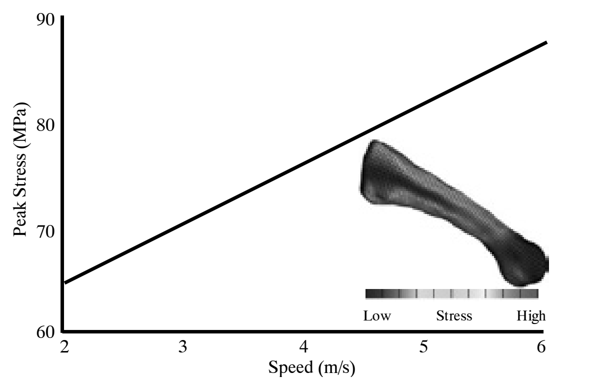

Figure 2.

These stress estimations are right in line with those that have been measured experimentally (Milgrom, 2001). Loading cycles for a given mileage/intensity combination was determined using the relationship between stride length and speed reported by Mercer et al., (2005). The number of cycles to failure for a given intensity was determined using the fatigue relationship reported by Carter and Caler (1985). The relative risk of stress fracture for a particular mileage/intensity

combination was defined as the number of loading cycles divided by the number of cycles to failure. It can be seen that the relationship between running volume and failure risk is a linear one-to-one relationship (Figure 3).

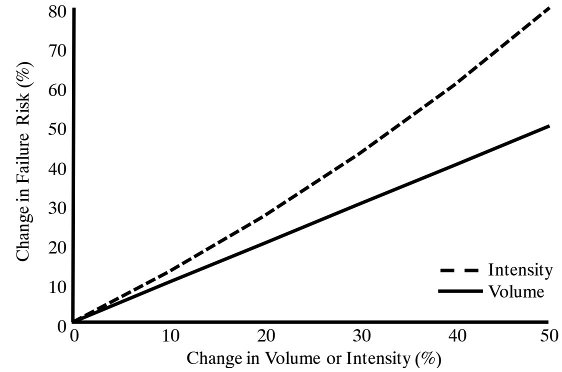

Figure 3.

On the other hand the relationship between running intensity and failure risk is a nonlinear relationship that increases rapidly at higher stress magnitudes. These data indicate that it is safer to increase training volume rather than training intensity during the initial stages of a new running regimen.

The logical question to ask is "How much of an increase in training volume or intensity is too much?" Unfortunately this is a difficult question to answer – we are aware of only one randomized controlled study that has examined the effects of a progressive increase in running volume on the frequency of overuse injury. In a study by Buist et al. (2008), 264 novice runners were assigned to a "graded" 13-week training program that progressively increased running mileage 10% per week. Overuse injury rates amongst the graded group were compared to a group of 268 controls that performed a "standard" 8-week training program. Intensity was not monitored but participants were told to run at a pace at which they could carry on a conversation without breathlessness. The frequency of overuse injury was not different between the graded (20.8%) and standard (20.3%) groups. Thus, to reduce the occurrence of overuse injury, increases in training volume per week need to be less than 10%, with increases in training intensity being lesser still.

FUNCTIONAL ADAPTATION

It has been known for centuries that biological tissues will adapt to their mechanical environment, a process known as functional adaptation. When mechanical loads are beyond those experienced during habitual activity, the tissue will adapt its structure to better resist these loads. Tendon and ligament will increase their cross sectional area, stiffness, and strength (Hayashi, 1996; Wren et al., 1998). Cartilage will increase its thickness, stiffness, and proteoglycan content (Kiviranta et al., 1987; Säämänen, 1987). Bone will increase its mineral content, density, stiffness, and strength (Notomi eta l., 2000; Rubin & Lanyon, 1985). These specific types of adaptations will either reduce the stress associated with a particular activity or improve the fatigue life associated with a particular stress level (i.e., a shift in the S-N curve up and to the left). The exact mechanism by which the process of functional adaptation occurs is still a topic of debate. On the other hand we have a relatively thorough understanding of exercise patterns that may be adopted to exploit this process.

Much of what we know about functional adaptation comes from the study of bone. Bone adaptation increases proportionately with stress magnitude (Rubin & Lanyon, 1985) and this response is enhanced when stress is applied at a faster rate (O'Conner & Lanyon, 1982). Thus, activities that generate high impact forces such as jumping are better than those that generate low impact forces such as walking. Repetitive loading quickly "saturates" the anabolic effects of mechanical stress so that each loading cycle has a lower influence on functional adaptation than the previous cycle (Rubin and Lanyon, 1984; Umemura et al., 1997). Turner and Robling (2003) demonstrated that bone's sensitivity to mechanical stress is proportional to $1/(N+1)$, where N is the number of loading cycles during a bout of activity. The anabolic effect of loading is enhanced when proper recovery periods are utilized (Robling et al., 2000, Robling et al., 2002; Turner and Robling, 2003). By providing recovery periods between loading bouts, it is assumed that the sensitivity to loading is restored. Sensitivity doubles after a four hour recovery period, but twenty-four hours of recovery is necessary for full sensitivity restoration.

The functional adaptation of biological tissue other than bone has been studied to a lesser extent, but it is reasonable to assume that similar rules exist for tendon, ligament, and cartilage. More frequent, but shorter-duration, exercise bouts have been shown to increase stiffness and strength of ligaments compared to less frequent, longer-duration bouts (Cabaud et al., 1980). Additionally, theoretical models of tendon and ligament adaptation have shown strong agreement with experimental results by assuming that the functional adaptation process depends on loading magnitude much more than the number of loading cycles (Wren et al., 1998).

SUMMARY AND RECOMMENDATIONS

It can be stated that all overuse injuries result from training errors (Hreljac, 2005). Although underlying biomechanical and anatomical factors may increase one runner's risk of injury compared to another, there is no doubt that every overuse injury can be avoided by simply not training. This is not a practical option for the competitive runner. However, the information presented in this review suggests that the occurrence of overuse injury can be reduced by adopting some sensible training strategies during the first few weeks of a new running regimen.

The longstanding "10% rule" for increasing volume may be too high. When large increases in running volume are required, as is the case for base training, an accompanied reduction in running intensity would be highly beneficial. The reduced intensity will lessen the stress experienced by biological tissue, thereby increasing the number of cycles to failure. At the very least, running volume and intensity should never be increased concurrently, and long rest periods should be encouraged to assure that the tissue is provided uninterrupted time for microdamage repair.

Despite its many positive health benefits, long-distance running may not be an optimal form of exercise from a functional adaptation standpoint. For example, 95% of bone's sensitivity to loading is lost after only 20 loading cycles. Breaking up the running regimen into several shorter sessions during the day would improve tissue integrity through adaptation, and at the same time allow more time for repair. At least four hours should be allotted between each running session to assure that sensitivity to loading is being restored. Supplementing the running regimen with tissue strengthening exercises, such as weightlifting, with incorporation of high impact activity, such as plyometrics, would be beneficial. As the tissue adapts to the mechanical loads placed upon it over the course of the first few months, training intensity could then be increased. Activities such as basketball and soccer would seem like ideal activities for staying fit in the off-season. The multidirectional loading component of these activities will assure the tissue is exposed to novel loading environments that enhance the functional adaptation process.

Finally, because overuse injuries result from cumulative tissue trauma through repetitive use, they will rarely occur without premonitory symptoms of injury (e.g., localized pain, "hot spots", etc.). Runners should be encouraged to pay close attention to the "language of their body." When pain begins, training should be ceased, tissue remodeling will occur, the fatigue damage will be repaired, and training may be resumed.

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Table 1. Fatigue behavior of various biological tissues. Stress values are in units of MegaPascals (MPa).

Tissue	Relationship between cycles to failure (N) and stress (S)	Typical stresses experienced during running	% change in cycles to failure with a 10% change in stress
Tendon	$N = 6.99\times10^{6} \cdot 10^{-(S/14.8)}$ [1] $N = 2.82\times10^{11} \cdot e^{-(S/2.53)}$ [2]	60-110 [7]	150-7,500
Cartilage	$N = 4.58\times10^{13} \cdot 10^{-(S/1.83)}$ [3] $N = 1.63\times10^{17} \cdot 10^{-(S/1.65)}$ [4]	5-10 [8]	100-300
Bone	$N = 1.36\times10^{14} \cdot S^{-5.342}$ [5] $N = 4.51\times10^{16} \cdot S^{-6.6}$ [6]	30-90 [9]	75-100

For cartilage, the relationship between cycles to failure and stress are assuming a 20 year old person. References: [1] Schechtman & Bader, 1997; [2] Wren et al., 2003; [3] Weightman, 1976; [4] Weightman, 1978; [5] Carter et al., 1981; [6] Carter & Caler, 1985; [7] Komi et al., 1992; [8] Brand, 2005; [9] Milgrom et al., 2001.

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Selected Cognitive Strategies and Running Economy: A Brief Review and Future Research Recommendations

Erik Lind, Ph.D. & Courtney Place, CPT

ABSTRACT

The economy of running is of critical interest to the competitive runner and his or her coach as it is an important factor in running performance. Running economy is a synchronization of factors related to the runner's physiological, biomechanical, and psychological characteristics. While considerable attention is still given to the physiological and biomechanical properties of running economy, the influence of psychological processes, in particular cognitive strategies, remains in need of elucidation. This purpose of this review is to provide a brief overview of selected cognitive strategies and the influence of each strategy on running economy. Finally, future research recommendations are provided to help guide a better understanding of cognitive strategies and the potential impact on running economy.

INTRODUCTION

The economy of human locomotion, in particular running, reflects a constellation of physiological, biomechanical, and psychological factors that ultimately influence the performance of the runner. Running economy takes into consideration the metabolic demands of the running effort and pace at which the effort is undertaken, and has traditionally been defined as submaximal oxygen consumption (VO2) at a given running velocity (Daniels & Daniels, 1992; Morgan & Craib, 1992; Pate, Macera, Bailey, Bartoli, & Powell, 1992), although more recent research may provide a more accurate expression using caloric unit cost (Fletcher, Esau, & MacIntosh, 2009). The concept of running economy is an important consideration for competitive middle- and long-distance runners and for coaches in monitoring the progress of a runner, evidenced in the fact that one study noted that 65% of the variance in 10 km race performance could be attributed to the running economy of a runner (Conley & Krahenbuhl, 1980). Awareness of and/or changes to the running economy of a runner may help in evaluating whether he or she is adapting to a training stimulus as planned. For example, it has been suggested that a positive change of 2.4% is required before one may assume improvement in running economy (Saunders, Pyne, Telford, & Hawley, 2004).

Given the multidimensional nature surrounding the concept of running economy and its importance in determining athletic performance, it is not surprising that scientific symposia and special issues in scientific journals have been devoted to reviewing the extant literature and elucidating research questions (Morgan, 1991). Much of what is currently known about running economy comes from research examining physiological and biomechanical factors related to running economy. Physiologically, studies have noted that better running economy is observed with lower maximal oxygen consumption and cardiorespiratory demands, lower age, and greater body mass (Pate et al., 1992), improved muscle strength via explosive resistance training (Paavolainen, Häkkinen, Hämäläinen, Nummela, & Rusko, 1999), exposure to a range of moderate-altitude training and living between 1,500 m and 2,500 m (Levine & Stray-Gunderson, 1997; Saunders, Telford, Pyne, Cunningham, Gore, Hahn, & Hawley, 2004), and changes in muscle-specific creatine kinase gene polymorphism (Zhou, Hu, Liu, Gong, Xi, & Wen, 2006). From a biomechanics perspective, investigations have shown that a decrease in surface stiffness (Kerdok, Biewener, McMahon, Weyand, & Herr, 2002) may improve the economy of movement in a runner, possibly due to changes in biomechanical properties in the lower limb region, specifically the Achilles tendon length (Hunter, Katsoulis, McCarthy, Ogard, Bamman, Wood, et al., in press; Scholz, Bobbert, van Soest, Clark, & van Heerden, 2008) and flexion/extension characteristics of the knee and ankle (Hunter et al., in press).

Conversely, much less is known about the role psychological processes play in the economical movement of a runner. This is surprising given the critical interplay between physiological and psychological factors involved during competitive running and training. For example, Williams et al. (1991) noted that running economy appeared sensitive to fluctuations in mood state. Specifically, decrements in running economy (as measured by increases in mean VO2) were observed as mood scores worsened. Crews (1991) reviewed the influence of psychological states and running economy and noted that one mood state, tension, seemed to show a strong relation with economical running in that reduced tension, whether self-reported or experimentally manipulated, improved

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running economy. Martin el al. (1995) further corroborated this finding in their study of running economy and attentional focus. The authors noted that runners with a more habitual inward attentional focus (i.e. focusing on bodily cues and sensations) were more economical compared to a group with a more outward attentional focus (i.e. observing his or her natural surroundings). Since running economy is related to the intensity of the training run and that affective responses (a precursor to mood) are sensitive to intensity levels as well (Ekkekakis & Petruzzello, 1999), this would suggest that any strategy that might cognitively manipulate the perceptions of effort of a runner during a training bout might also influence his or her running economy.

Thus, the aim of this review is twofold: (i) to examine the efficacy of selected cognitive strategies on running economy, and (ii) to provide future research recommendations to help guide competitive runners and coaches in their understanding of how cognitive strategies factor into economical running.

METHODS

To locate studies on the use of cognitive strategies during bouts of running, computer searches were conducted in scientific databases (PsycLit, PubMed, Google Scholar) using the terms (and combinations thereof): running economy, attentional focus, association, audio-visual, biofeedback, dissociation, focal awareness, internal focus, external focus, music, and self-talk. Furthermore, the reference lists of the obtained articles were searched for additional studies relevant to the current review. Only a small number of studies related to running economy and cognitive strategies were selected for the review. This was done as it was deemed better to provide the reader with a broad and general overview of individual cognitive strategies rather than attempt an exhaustive account of the relationship between running economy and cognitive strategies. By examining selected strategies individually, it is the hope that the reader can draw certain conclusions regarding the broader spectrum of cognitive strategies as it pertains to his or her own interest.

In light of the number of cognitive strategies that have been examined in the sport and exercise psychology literature, it was deemed important to limit the current review to the more common strategies associated with running. As such, cognitive strategies such as hypnotic suggestion or imagery, or experimental cognitive manipulations such as interventions to alter self-efficacy were excluded from the current review.

SUMMARY OF FINDINGS

The following summary of findings highlight relevant observations pertaining to running economy and selected common cognitive strategies. The selected investigations in this section are thought to be representative of the type and nature of studies conducted on the subject, and characterize the patterns of findings one might expect with other related studies.

MUSIC

The role of music while exercising, in particular, has a long research history in human movement studies. Music has historically been associated with aesthetic, coordinated movements of both the athletic performer and exerciser (Höhne, 1979), suggesting a natural extension between musical rhythms and synchronized human movement (Brown, 1980; Karageorghis, 1999). "Listening to music" and "exercising" are commonly employed mood-regulating strategies (Stevens & Lane, 2000; 2001), and it appears that individuals select music appropriate to the situation and according to their arousal-based goal (North & Hargreaves, 2000).

Given the natural relationship between musical characteristics and human movement, one might expect listening to music to improve running economy. Some investigators have observed positive results. For example, Matesic and Cromartie (2002) reported that music resulted in faster 400 m lap running times for both trained and untrained runners. Moreover, untrained runners ran a faster lap time with music than did the trained runners under the same condition. Moreover, Miller and Donohue (2003) noted that listening to music prior to running a 1.6 km cross country course produced times 5 sec faster (effect size = 0.76) in a group of high school runners. However, not all studies appear to be in agreement. When performance has been measured as running efficiency (Beaver, 1976), in particular stride frequency and stride length, it appears that music has limited effectiveness as running speeds increase. Loucks (2000) noted that a 20-min treadmill run between 65% and 85% of maximal heart rate showed no difference in perceptual or cardiovascular measures across different music tempo (beats per minute) conditions. Brownley et al. (1995) examined the differences in affective and cardiorespiratory responses in trained versus untrained runners when listening to music or no music during treadmill exercise during three consecutive trials at low, moderate, and high intensities. Within each exercise intensity condition, respiration frequency was significantly higher in the music conditions. Likewise, there was a trend for higher respiration frequencies in the untrained, but not trained, runners during the fast music condition compared to a sedative music condition and a no music condition. Macone et al. (2006) found that, although music resulted in longer times to exhaustion while running at 75% of heart rate reserve, there was no difference in mood state measures as compared to a no music condition, and female runners reported greater feelings of fatigue when running with music compared to no music.

ASSOCIATIVE ATTENTIONAL FOCUS (I.E. BIOFEEDBACK)

The way association and dissociation have been defined over the years has varied. Originally, the attentional focus strategy of association was characterized as the focus on bodily sensations necessary for optimal performance (Weinberg et al., 1984) and, more specifically, on physical sensations emanating from changes in respiration, temperature, and muscular fatigue (Morgan, 1978). Biofeedback and self-talk statements focusing on running form or to relax certain muscles, for example, would be considered an associative strategy. At the other end of the attentional focus spectrum, dissociation was characterized as a cognitive process of actively "blocking out" sensations of pain or discomfort related to physical effort. As described by Morgan (1978), an individual who dissociates "purposefully cuts himself off from the sensory feedback he normally receives from his body" (p. 39; sexist language retained from the original). Defined as such, listening to music while running would be a common example.

Smith et al. (1995) observed that a group of experienced distance runners identified as more economical in their running showed less use of dissociative strategies and relied more on relaxation compared to a group identified as less economical. Hatfield et al. (1992) noted that a biofeedback intervention significantly reduced the ventilatory response observed in a group of runners performing just below the ventilatory threshold compared to both a distraction condition and a control condition. Donohue et al. (2001) found that associative strategies were more beneficial in improving running performance in a group of adolescent cross-country runners performing a 1 km run at a self-selected pace compared to motivational self-talk statements and thought content comments.

SELF-TALK

One advance in the study of self-talk has been a clearer operationalization of the concept. One of the primary obstacles to understanding self-talk within sport and exercise psychology has been accurately defining the term "self-talk." To this end, a critical review by Hardy (2005) advanced the definition by Hackfort and Schwenkmezger (1993), which characterizes self-talk as a "dialogue [through which] the individual interprets feelings and perceptions, regulates and changes evaluations and convictions, and gives him/herself instructions and reinforcement" (p. 355). Applying this definition to running economy may help in the understanding of how certain dimensions of self-talk may factor into more economical movement and improved running performance. When compared to preferred music, listening to motivational and statements on running technique produced faster running performances on a 1.6 km course in adolescent runners (Miller & Donohue, 2003). Contrarily, Weinberg et al. (1984) observed no difference in heart rate and fatigue perceptions during a 30-min run at a self-selected pace. As the stimulus was a true submaximal effort, the authors further noted that it "…appears that rather than an "all out" run, subjects were pacing themselves somewhat and it is plausible that they were not sufficiently stressed, thus reducing the potential effectiveness of their particular cognitive strategy" (p. 30).

DISCUSSION

Running economy remains a topic of great interest across various exercise science disciplines. As more is learned about the factors that influence running economy, competitive runners and coaches will have more accurate and sensitive performance tools with which to work in developing better running economy. Given that running economy is a better predictor of running performancew than VO2max values, having a thorough grasp of running economy cannot be underscored enough.

Running economy has not been systematically studied within the sport and exercise psychology literature. Thus, it should not be surprising that the findings of this brief review are inconclusive as to the actual benefit of cognitive strategies on running economy. The extant literature on running economy and psychological processes has examined the subject utilizing various exercise intensities and performance markers, correlates of running economy, participant samples ranging from recreational to elite runners, and numerous self-report measures of psychological processes. In light of the lack of systematicity in the pursuit of our understanding on running economy, across all exercise science disciplines, it seems imperative that efforts be made to identify theoretical frameworks on which to study running economy and then begin examining testable hypotheses.

FUTURE RESEARCH RECOMMENDATIONS

The equivocalness of findings has been echoed in previous discussion on running economy (Martin & Morgan, 1992; Morgan & Craib, 1992). Moreover, some experts further suggested the need to examine running economy relative to the "…inherent characteristics…" of the individual (Daniels, 1985) and that additional data be gathered approaching near maximal efforts (Daniels & Daniels, 1992). Collectively, it appears that investigating running economy from a multidisciplinary perspective is the only consensus reached in the studies used for this review. In his opening discussion of the 1991 American College of Sports Medicine symposium on running economy, Morgan (1992) concluded that the concept is best addressed using a cross-disciplinary approach with testable hypotheses developed to understanding the mechanisms of economical running.

One possible approach that might shed light on the topic is the Dual Mode Model (DMM) developed by Ekkekakis (2003). This model was developed to better understand the affective responses to varying levels of exercise intensity, but the model also has certain features that make it applicable to understanding running economy. According to the DMM, affective and exertional responses during exercise performed at intensities below and proximally to the ventilatory threshold involve primarily cortical pathways. On the other hand, at intensities that exceed the ventilatory threshold and preclude the maintenance of a physiological steady-state, interoceptive afferent cues reach areas of the brain responsible for the elicitation of affective and exertional responses following direct, faster, routes, bypassing the cortex.

The attractiveness of this model lies in the fact that it examines any response of interest across a spectrum of exercise intensities, including those intensities levels typically studied in running economy investigations. Furthermore, the model provides testable hypotheses with regard to the relative efficacy of cognitive strategies, including those strategies excluded from the current review, at different levels of exercise intensity. Thus, the interested researcher could design experiments on running economy with identified physiological, biomechanical, and psychological dependent variables of interest and come away with a clearer understanding of the complex interaction that comprises running economy.

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Reassessing Velocity Generation In Hammer Throwing

Andreas V. Maheras, Ph.D.

Throws Coach at Fort Hayes State University - Hayes Kansas

ABSTRACT

In the hammer throw, the exertion of the force necessary to increase the horizontal velocity of the implement is thought to take place mainly when both the thrower's feet are in contact with the ground during the double-support phases of the turns. Coaches have therefore sought to maximise the duration and the effectiveness of the double-support phases while minimising the length of the single-support phases, when it is assumed that the thrower is preparing for the next double-support. However, as scientific understanding of the event has developed things have become less clear. It is now known that the horizontal velocity of the hammer is increased mainly in the winds or early part of the throw, when the thrower is stationary or rotating slowly, and that the observed increase in velocity during the turns is due not to a horizontal pull-push of the feet against the ground but to the addition of vertical velocity and a shortening of the hammer radius. Therefore, emphasis on the double-support phases may well be misplaced. Stressing that there is still much that is not known about the hammer throw, the author explains current understanding of the event in detail and makes recommendations for coaches to consider.

INTRODUCTION

The hammer throw movement starts with the execution of two or three winds, which are followed by three or four turns, in which the thrower rotates with the hammer in a synchronised fashion. During the winds and subsequent turns, the velocity of the hammer increases progressively until the moment of release following the last turn. The velocity of the hammer at release is a determining factor for the length of the throw. As the throwing movement progresses, three important features can be observed: 1) the circular motion of the hammer around the thrower, 2) the gradual change of the slope of the hammer's plane of movement, and 3) the horizontal translation of the thrower-plus-hammer system across the circle.

In the early part of the throw, the hammer's plane of movement is rather flat, however, it becomes steeper as the throw advances and it reaches a slope of approximately 40º during the last turn. The thrower keeps the hammer on its circular path by exerting a centripetal force, which is a force pointing towards the centre of the path of the ball and can be over 300kg during the last turn of a world record throw, through the wire to the centre of the ball. In turn, the wire exerts an equal and opposite force on the hands of the thrower, which tends to pull him/her forward (DAPENA, 1989).

The concept of hammer throw technique held by most coaches has long included the following two elements. First, the winds at the beginning of the throw have been seen as a preliminary movement with a much less important impact on the velocity of the hammer than the turns that follow. Consequently, relatively little attention has been paid to this element of the overall movement. Second, it has been thought that exertion of the force necessary to increase the horizontal velocity of the hammer mainly takes place when the thrower's feet are both in contact with the ground during the double-support phases of the turns. Coaches have therefore sought to maximise the duration and effectiveness of the double-support phases while minimising the single-support phases, when it is assumed that the thrower is in a recovery phase preparing for the next double-support.

However, as scientific understanding of the event has developed, the situation has become less clear. For a start, there is still much that we do not know. What we can see now is that the winds are the thrower's best opportunity to increase horizontal velocity and that vertical velocity is a very important component of the hammer's total velocity. We can also see that emphasis on the double-support phases may well be misplaced. This is not to say the double-support is unimportant, but there are certainly other aspects to increasing the velocity of the hammer at release that must be considered. In this article I will explain these statements in detail and make recommendations for coaches to take into account when thinking about hammer throw technique.

HAMMER THROW VS. TUG-OF-WAR

As the thrower-plus-hammer system advances across the circle, one may think that the thrower uses forces resulting from the friction between his/her feet and the ground to resist against being pulled forward, much like what happens in tug-of-war (WOICIK, 1980). However, the dynamics of the two activities are quite different. In hammer throwing, the reactionary forces that keep the hammer ball on its circular path, also serve to keep the thrower on his/her own, circular path. This implies that the thrower does not push forward on the ground in order to stay in place.

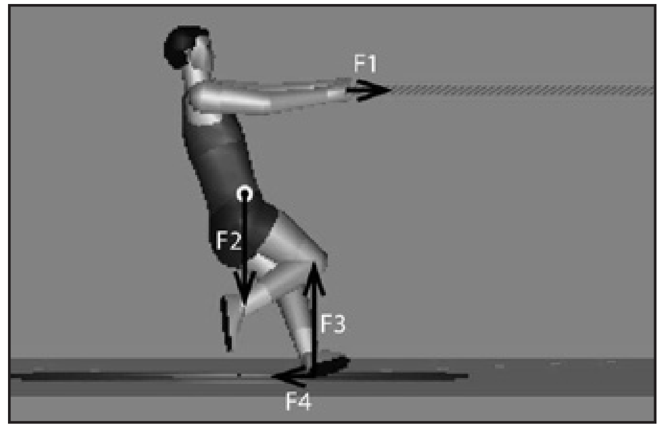

Figure 1: Forces on the athlete in a tug-of-war

Figure 1 shows what happens in what could be called a tug-of-war scenario (DAPENA, 2007). Here, F1 is the forward force made by the wire on the hands; F2 is the weight; F3 is the vertical force made by the ground on the foot; F4 is the horizontal force made by the ground on the foot. F2 is about the same size as F3, so they essentially cancel each other out; F1 is about the same size as F4, so they also cancel out. The sum of all the forces made on the thrower is approximately zero and he/she not moving at all (in a static condition). In other words, the body of the thrower experiences no linear acceleration.

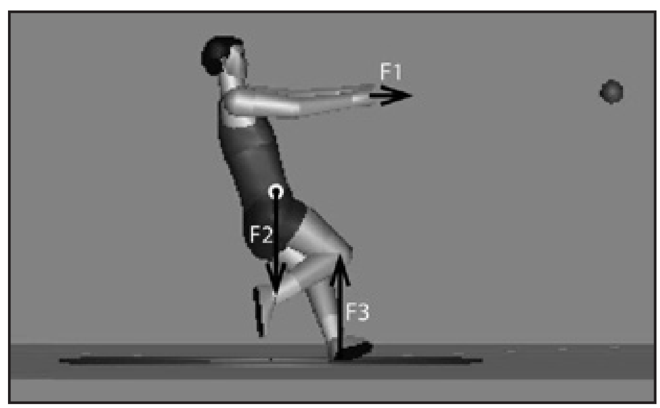

Figure 2: Forces on the thrower in hammer throwing

Figure 2, shows what really happens in hammer throwing. Here, force F4 is essentially missing. So forces F2 and F3 essentially cancel each other out, leaving us with force F1, which, indeed, accelerates the body forward. But this forward acceleration will not make the thrower actually translate forward and fall flat on his/her face. The reason is that the thrower (like the hammer) is rotating about the combined centre of mass (CM) of the thrower-plus-hammer system. In Figure 3 we see that the thrower's CM (yellow dot) is very close to the combined system CM (green dot), so the radius of the path (violet line) followed by the thrower's CM about the combined system CM is pretty small, the distance between those two dots. But the thrower's CM is indeed rotating about the combined system CM, and such a rotation (like any other rotation) requires a centripetal acceleration, a force to keep the body's CM following that short-radius circular path. And that force is exerted by the hammer on the hands through the wire, which we have called F1 in Figures 1, 2 and 3.

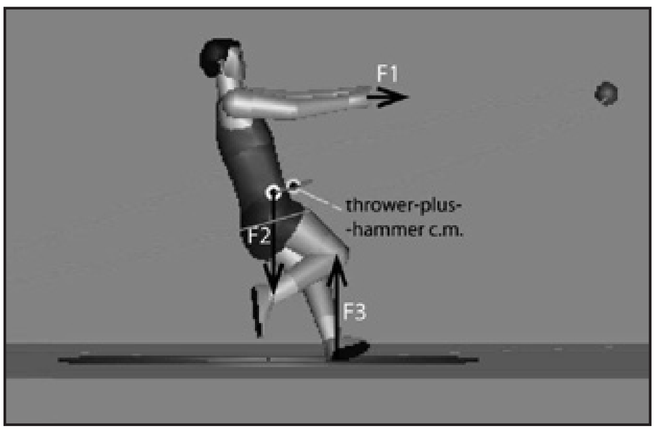

Figure 3: The combined centre of mass of the thrower-plus-hammer system

In the same way, the reaction to F1 is the force exerted by the hands on the hammer ball through the wire, and this reaction force (which we could call force F5 for example, but it is not drawn in the figures), is the centripetal force that keeps the hammer ball rotating about the combined system CM (the hammer's orange path).

The phenomenon described shows that some of the forces required to maintain the static balance of the tug-of-war athlete are not necessary for the dynamic balance of the rotating hammer thrower. It also shows the need for coaches to make a distinction between static and dynamic balance when dealing with hammer throwing.

THE "LONG DOUBLE-SUPPORT" MODEL

However, simply keeping the hammer on a circular path will not suffice. The thrower also needs to increase the velocity of the hammer. According to some authors (WOICIK, 1977; BLACK 3, 1980; WOICIK, 1980) hammer velocity in general can be increased most effectively during the double-support phases of the throw. It has been observed (DAPENA, 1984) that hammer velocity increases between the high and low points of its orbit, which roughly coincide with the beginning and the end of the double-support phase respectively. It therefore seems logical to assume that it is easier to produce a rotation about the vertical axis when both feet are in contact with the ground than when only one foot is in contact with the ground. It also seems logical to assume that the single-support phase is a recovery phase during which the athlete prepares for another double-support phase.

It follows that maximising the double-support phase and minimising the single-support phase is a prudent way to go about increasing force output in hammer throwing. One action that has been used to achieve this aim involves keeping the right leg close to the body. This enables the thrower to speed up during single-support and thus to plant his/her right foot sooner to start the next double-support. Another movement involves the landing of the right foot with the toe pointing towards the 2700 azimuthal angle instead of the 00 angle. This will also allow the thrower to plant the right foot earlier, again shortening the single-support phase and lengthening the double-support phase. The thinking behind both these movements is based on the simple model:

- double-support = when the thrower can increase hammer velocity,
- single-support = a waiting period.

However, just because two quantities coincide in time does not mean that one causes the other. In fact, no direct cause and effect link has been shown between the double-support phase and the increase in hammer velocity (DAPENA, 1989). Moreover, film analysis data may not fully support the theory either (GUTIERREZ, SOTO & ROJAS, 2002). It is possible then that the association between hammer velocity increase and the double-support is spurious and coincidental and, importantly, that there may be other factors involved.

One such a factor may be gravity. As the hammer moves upwards and downwards in its sloped plane of movement, gravity naturally will affect its velocity.

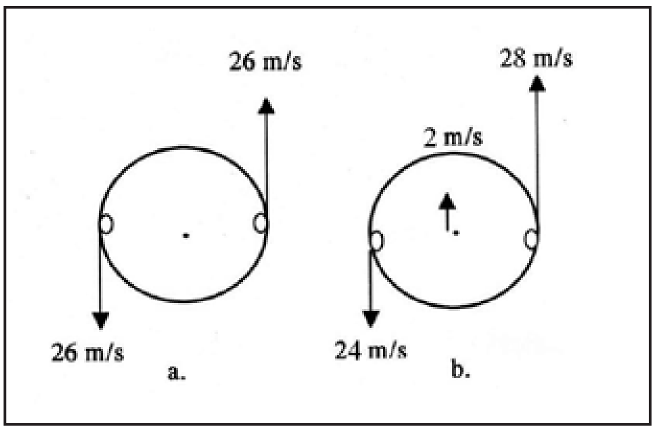

Figure 4: Relative velocity of an item rotating around a circular path (a) without and (b) with horizontal translation

Another factor may be the horizontal translation of the thrower-plus-hammer system. We can see this in Figure 4 (a), where we assume an item is attached at the edge of the circular table rotating anticlockwise around itself (vertical axis) and that the linear velocity of the attached item is a constant 26 m/s. Subsequently, if we push the table horizontally at a constant velocity of 2 m/s, as shown in Figure 4 (b), the instantaneous velocity of the item itself will be 28 m/s relative to the ground (26+2) when the item reaches the 900 azimuthal angle, because the item is moving in the same direction as the system's CM, and 24 m/s relative to the ground (26 – 2) when the item reaches the 2700 azimuthal angle, because the item and the system's CM are now moving in opposite directions. The velocity then will fluctuate between 24 and 28 m/s throughout the turns because there is a combination of rotation at a constant angular velocity and forward translation at a constant linear velocity. A similar phenomenon may occur during hammer throwing, with the hammer ball being the item rotating in a circular path while simultaneously there is a horizontal translation of the thrower-plus-hammer system across the circle. Such a combined movement will affect the velocity of the hammer.

These two factors, gravity and horizontal translation, can be mathematically accounted for and subsequently removed from consideration when the hammer velocity is calculated (DAPENA, 1984). Under these circumstances, in some throwers, the fluctuations observed in the velocity of the hammer disappeared. Yet in others, there was still indication of this fluctuation. Thus, it is possible that other factors may also be affecting hammer velocity in some throwers.

HORIZONTAL AND VERTICAL VELOCITY GENERATION

Another problem with the "long double-support"

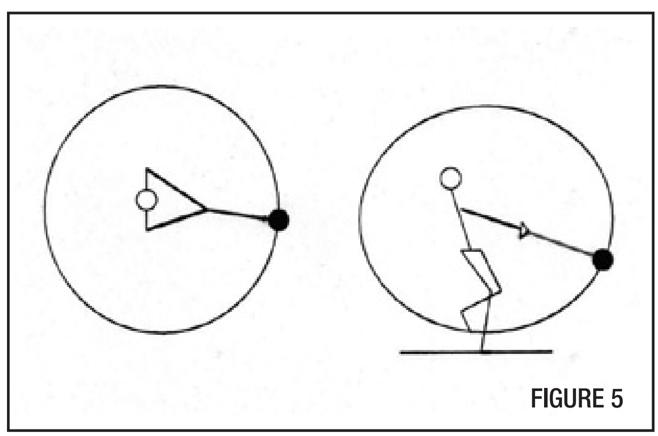

Figure 5: Rotation about a vertical axis (left), view from overhead, and rotation about a horizontal axis (right), view from the 00 azimuthal direction-front

hypothesis is that it only considers rotation about the vertical axis. This implies that the motion of the hammer ball is only on a horizontal plane (WOICIK, 1980). In reality, however, the motion of the hammer also takes place about the horizontal axis, which implies motion of the ball on a vertical plane (Figure 5). It is clear then, that to increase the velocity of the hammer, a thrower needs to obtain a torque not only about the vertical axis, but also about the horizontal axis.

What makes this last statement even more important is the observation that the majority of the increase in velocity during the turns is associated with generation of torque about the horizontal axis. In other words, the majority of velocity increase during the turns is vertical velocity and only a small part of the increase is horizontal velocity (DAPENA, 1989). It is true that the horizontal velocity of the hammer can be increased much more effectively during double-support than during single-support. However, this is only the case when the thrower is rotating very slowly. When the thrower is rotating fast, it is impossible to increase horizontal velocity in either of the support phases (DAPENA, 1989). Instead of thinking that double-support = good, because only in double-support can a thrower exert torque and, single-support = bad, because in single-support a thrower cannot exert any torque, one may need to modify this thinking accordingly (DAPENA, 2007).

The "big picture" of what happens in hammer throwing, is that during the winds (when the speed of rotation is slow and the thrower is all the time in double-support), the thrower increases the horizontal velocity of the hammer. But by the time the turns start, the hammer is turning fairly fast (just for reference here, at 15 m/s), and the body of the thrower is also turning pretty fast. As a result, during the turns, no more horizontal velocity of the hammer can be generated, regardless of whether it is at an instant in which the thrower is in single-support or at an instant in which the athlete is in double-support.

If, for the sake of argument, the thrower were forbidden to produce any vertical velocity, the velocity of the hammer at release would be 15 m/s, the same as the velocity of the hammer at the start of the first turn.

But the thrower is not forbidden to generate vertical velocity. Let's say, for example, that during the turns the thrower generates 14 m/s of vertical velocity. This would be the vertical velocity at the steepest point of the path, and it would increase gradually from one turn to the next; for example, from 0 m/s to 4 m/s to 8 m/s to 11 m/s to 14 m/s in the four successive turns. At the end of the last turn the hammer would have this 14 m/s of vertical velocity plus the 15 m/s of horizontal velocity already mentioned. The total velocity would be equal to the square root of (152 + 142), or 20.5 m/s.

What we see in this example is that the hammer did indeed gain velocity during the turns but it did not gain any horizontal velocity, all the gain was in the vertical. Importantly, this gain of vertical velocity had nothing to do with the thrower being in double-support or in single-support. Whether the thrower is in single or double-support matters only in relation to gains of horizontal velocity, and then it would apply only when the horizontal velocity was not yet very high (i.e., during the winds, not during the turns). In other words, the gains in total velocity that occur during the turns are linked to changes in the vertical velocity, which can be produced when the thrower is in double-support or in single-support.

According to DAPENA (1989 and 2008), the torque in the vertical direction (about the horizontal axis) is generated during double-support as follows: first, the thrower presses harder on the ground with the left foot than with the right foot and/or second, the thrower generates vertical forces on the ground with both feet, but keeps the CM of the thrower-hammer

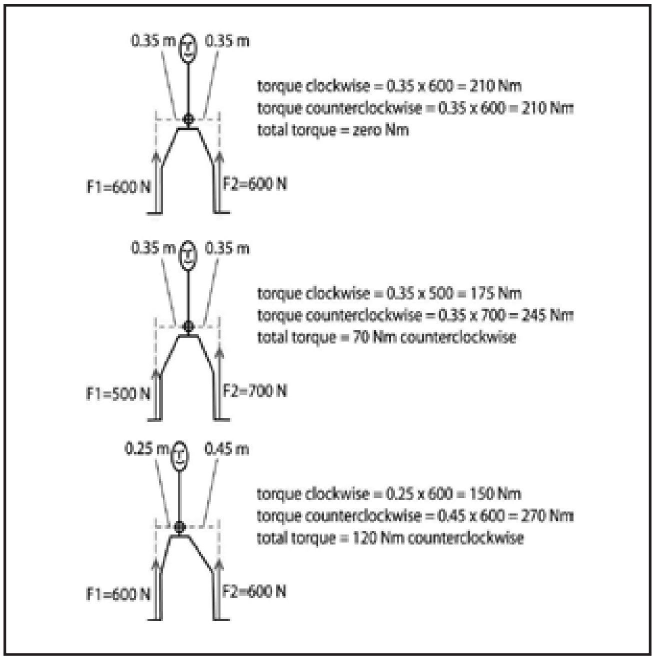

Figure 6: Torque generation during double-support
Note: The terms "torque clockwise" and "torque anticlockwise" refer to those directions from the reader's point of view not the thrower's point of view. Therefore, a "clockwise torque" refers to a tendency for a rotation towards the thrower's own left and "anticlockwise torque" refers to a tendency for a rotation towards the thrower's own right.

system closer to the right foot than to the left foot, instead of half-way between them.

In Figure 6 on top, when the CM is half way between the right and left leg and both feet exert the same forces on the ground, the amount of torque produced in the anticlockwise or the clockwise direction is the same and therefore the total amount of torque produced equals zero. In the middle of Figure 6, the CM is still halfway between the two legs but the left foot exerts a larger torque and the net effect, the difference between the two directions, is a total torque pointing clockwise, from the thrower's point of view, which effectively tends to cause the thrower to rotate in that direction (towards his/her right). From this position if the thrower accidentally let go of the hammer, he/she would fall towards his/her right side.

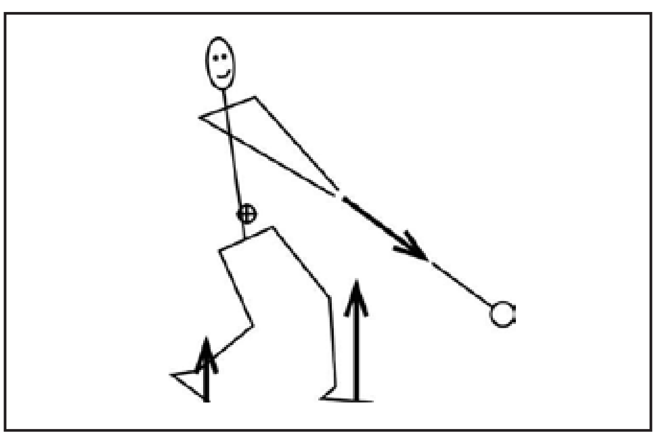

Figure 7. Forces exerted by the feet on the ground and reactionary force exerted on the hands by the cable during double-support

However, the thrower does not let go of the hammer and by pulling on the cable, he/she will give the hammer an upward acceleration. In turn, the cable will make a reaction force on the thrower's hands (Figure 7). This reaction force will exert a clockwise torque on the thrower and it would normally make him/her rotate toward his/her left (or forward if the thrower is already facing toward the 90º azimuthal angle). However, as discussed earlier, the forces on the feet are such that they produce a net anticlockwise torque (towards the thrower's right) about his/her CM and the clockwise torque exerted by the hammer on the hands about his/her CM (towards the thrower's left) simply cancels out the anticlockwise torque exerted through the feet. The thrower manages to give the hammer an upward acceleration without losing balance, because the total torque on him/her will be zero.

The eventual practical benefit of the left foot pressing harder on the ground is that the thrower will be able to pull harder upward on the hammer during the upward part of the hammer trajectory resulting in an even greater upward acceleration due to that pulling. On the other hand, if the thrower were to press harder with the right foot (instead of the left as we have discussed so far), this would result in a tendency for the thrower to rotate to the left, and the reaction cable force (which also makes the thrower rotate to the left) will add to the forces made on the feet and the thrower will lose balance and fall to the left.

A detail that needs to be mentioned here is that, during most of the time when the hammer ball is travelling upward, the athlete will be not in double-support but in single-support. The uphill motion will occur approximately between the 0º and 180º azimuthal positions of the hammer. During this ascent, the thrower will be in double-support from azimuthal angle of 0º of the hammer to azimuthal angle of 50º or so (very rough value), and from there all the way to 180º he/she will be in single-support. In other words, during most of the uphill travel of the hammer the thrower will be in single-support.

Finally, at the bottom of Figure 6, the combination of the location of the CM, which is now more towards the right foot, and the amount of torque generated

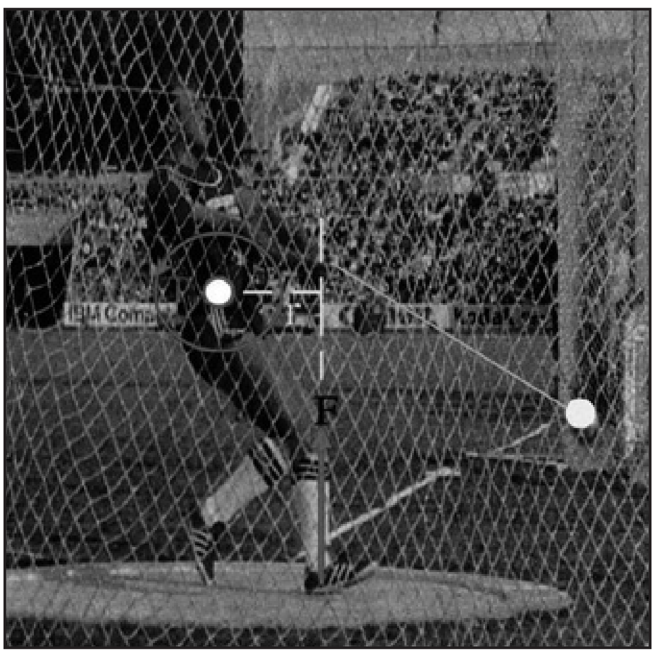

Figure 8: Vertical force (F) made by the ground, and anticlockwise torque (T) produced around the longitudinal Y-axis during single-support
Note: This axis would be perpendicular to the page and is passing through the centre of mass (white dot at the right hip area). The torque about the centre of mass would be the product of (r) x (F), and the torque itself would be as indicated by the curved red arrow. The torque vector would be pointing along the Y-axis, from the page toward the reader.

by the feet, produce an even greater net anticlockwise torque.

During single-support, the torque is produced automatically because the point of support, which is the left foot, is not directly under the thrower, and the reactionary vertical force generated by the ground on the left foot exerts a torque about a longitudinal axis passing through the CM (Figure 8). To better picture this effect, we can picture someone standing with both feet on the ground, if they were to remove the right foot without making any other changes, would fall toward the right. However, this is not the case during hammer throwing because the torque that the thrower receives from the ground is transmitted to the hammer. This way, the thrower does not fall despite the fact that the point of support (the left foot) is not directly beneath his/her CM while at the same time the hammer accelerates.

Another point to add here is that the thrower can (and normally does) reduce the radius of rotation of the hammer ball somewhat as the throw progresses from turn one to turn four. This will produce some increase in the total velocity of the hammer ball. In the example we have been using the total velocity of the ball at the end of the last turn won't be 20.5 m/s, but closer to 24 m/s.

CONCLUSIONS

Coaches implicitly tend to think in terms of "distance of force application" to increase horizontal velocity and that force application can only occur in double-support. However, it is an over-simplification to consider that in hammer throwing there is rotation about a vertical axis only. The rotation occurs about an inclined axis, which implies rotation about both a vertical, and a horizontal axis. The rotation about the vertical axis (horizontal velocity) can best be produced during the double-support phase, but only if the thrower is rotating slowly. The rotation about the horizontal axis (vertical velocity) can be produced both during the single-support and double-support phases and thus, single-support phase does not have to be a “recovery” phase.

If we were to assume that the forces generated in hammer throwing (dynamic balance) are similar to those observed in tug-of-war (static balance), then in the double-support phase in hammer throwing it would be possible to push forward on the ground with the left foot and pull backward with the right foot. As a result there would be an increase of the angular momentum of the combined thrower-plus-hammer system about the vertical axis. From this, one could further infer that in single-support it would be much more difficult to increase the angular momentum. Therefore, under those conditions, to generate the maximum possible amount of angular momentum about the vertical axis during the throw, a thrower would want to maximise the time in double-support within each turn. As explained earlier, to do this, there would be a need to minimise the time in single-support. This means that the thrower would want to take off late (for example at the 90º azimuthal angle) and land early (for example at the 220º or 230º azimuthal angle).

However, in reality, the forces generated in hammer throwing are not similar to those of a tug-of-war and the “long double-support” model places the emphasis on the wrong concept. The reason can be found in the sentence in the previous paragraph where it says: “to generate the maximum possible amount of angular momentum about the vertical axis during the throw, a thrower would want to ...”. It turns out that generating the maximum possible amount of angular momentum about the vertical axis is NOT the main goal of the hammer thrower (DAPENA, 2008).

Why? Because during the turns the thrower is turning so fast already that it is nearly impossible to push forward on the ground with the left foot and pull backward with the right. Therefore the angular momentum about the vertical axis increases very little. Putting the emphasis on this is focusing on something that is going to be of a small value no matter what. Of course, the actual value of angular momentum about the vertical axis will be big even if the gain during the turns will be small. But this momentum will have been generated, almost all of it, during the winds, with very little of it being generated during the turns. So the most important thing that is happening during the turns is not the change in the angular momentum about the vertical axis, it is the change in the angular momentum about the Y-axis, which is the axis aligned with the midline of the throwing sector and, in turn, this is linked to the changes in the vertical velocity of the hammer.

Following the discussion above, hammer throwers cannot afford to take it easy in the preliminary phase (the winds). They need to produce a lot of hammer velocity already in the winds. Of course, they have to stay under control, but they still need to be very dynamic. Moreover, although the “flatness” of the plane of the winds has been addressed before (e.g. EBERHARD, 1990) it needs to be emphasised that from a mechanical point of view, throwers need to keep the hammer ball on as flat a path as possible.

There will be time later (during the turns) to add vertical velocity but only a small amount of horizontal velocity can added in the turns so it must be the focus during the winds.

To be clear, we are not saying that a thrower cannot increase hammer velocity in double-support. What we are saying is that a thrower can increase hammer velocity BOTH in double-support and in single-support. What has been observed is that the increase in the velocity of the hammer ball during the turns is due mainly to the addition of vertical velocity, and in part also to the shortening of the hammer radius. But the increase is not due to a horizontal pull-push mechanism of the feet against the ground; that was something that stopped happening with the end of the winds. Moreover, neither the increase of vertical velocity nor the shortening of the hammer ball radius are favoured by being in double-support. That is why, from this point of view, the achievement of a long double-support during the turns may not be as important as many think.

If maximising double-support may not be the best approach in hammer throwing, then what would the alternative be? The answer is we don't know (at least experimentally) the optimal pattern in regard to double-support versus single-support. In the final turn of a hammer throw, it is possible that the thrower does not increase the hammer velocity much during the downward part of the hammer's path (from, say, the 2400 azimuthal angle to the 00 azimuthal angle), and that the only hammer velocity increase occurs between the 00 azimuthal angle and release (at the azimuthal angle of 700 or 900 or something like that). In such case, earlier landing of the right foot would not contribute to an increase of the hammer velocity. However, we cannot be sure about this part because here we may be getting near the limits of applicability of the theories and data to actual throwing, but it is perfectly possible.

Again, with all this, we are not trying to denigrate the double-support. We are just trying to say that the single-support is not necessarily the "poor relative" and therefore, it is not the guaranteed wasteland that we used to think. In other words, we cannot be sure anymore that maximising the double-support time is the optimum. Maybe maximising double-support is still the optimum. Or maybe maximising single-support is the optimum. Or maybe some intermediate between the two is the optimum. We simply don't know.

RECOMMENDATIONS

Based on the discussion above, I can make the following recommendations to coaches:

1) During the winds (which are all in double-support), the thrower can increase both horizontal velocity and vertical velocity but for maximum effectiveness needs to concentrate on increasing horizontal velocity during this period;

2) During the single-support phases of the turns, the thrower can increase vertical velocity, and he/she needs to do so;

3) During the double-support phases of the turns, the thrower can also increase vertical velocity and he/she needs to do so.

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Practical Lessons on Running and Jumping from Computer Simulations

Ross H. Miller Ph.D. and Graham E. Caldwell Ph.D.

Department of Mechanical & Materials Engineering - Queen's University, Kingston, ON, Canada

Department of Kinesiology - University of Massachusetts, Amherst, MA, USA

ABSTRACT

Running and jumping are important movements for the success of athletes. Researchers in biomechanics, motor control, and sports science often use computer modeling and simulation to study the optimal performances of these movements. Simulation techniques have not been widely applied to actually assessing and improving athletic performance, although the potential for this application exists. In this review, we (1) present an introduction to the basic concepts of modeling and simulation with the athlete and coach in mind, (2) summarize the unique information that has been gained over the last 30 years from computer simulations of human running and jumping, and (3) offer suggestions on how coaches and athletes can use this information in practice to improve performance.

INTRODUCTION

Running and jumping are fundamental athletic skills that are important for athletes in nearly every sport. Although situational factors and constraints influence the goals of these movements in specific instances (Glazier & Davids, 2009), in general athletes attempt to jump as high as they can or run as fast as they can. As sports scientists, coaches, and athletes, we may wonder if an athlete is achieving these goals optimally: are they really jumping as high as possible or running as fast as possible? Are they doing so in an efficient way? Are there simple (or not-so-simple) adjustments that could be made to improve performance?

There are many ways to address these questions through science and training, and indeed these questions drive the work performed by successful coaches in all sports. One approach that has been used frequently by researchers but seldom by coaches and athletes is the use of computer simulations (Hatze, 1983; Vaughan, 1984; Neptune, 2000). Therefore, the purposes of this review are (1) to provide an introductory background on musculoskeletal modeling and computer simulation so that coaches and athletes can be well-educated consumers of such research, (2) to highlight the unique information on running and jumping that has been gleaned from computer simulations of these movements, and (3) to suggest how coaches and athletes can use this information to improve athletic performance.

OVERVIEW OF COMPUTER MODELING AND SIMULATION

While the ability to create models and perform simulations is not required to be a consumer of simulation-based research, a general understanding of the terms, techniques, and procedures involved is useful for understanding the work. A model, by the most general definition, is a system that is used to represent another system. A model can be physical, conceptual, or mathematical in nature. The great majority of research in biomechanics, motor control, and sports science involves either a conceptual or mathematical model. Typically a model is much less complex than the original system so that it can be more easily understood. In general the ideal model is the simplest one that can still address the research questions. For example, the basic flight pattern of a ball or shot can be understood by the conceptual model of an airborne object under the influence of gravity alone. A mathematical model represents the original system as a set of equations; in the ball/shot example, these equations would be the relatively simple equations of projectile motion. A computer model is a mathematical model created in the form of a computer program. Most mathematical models of human movements are also computer models because, unlike simple projectile motion, the equations are too complex to solve by hand. To study athletic performance, we can create a musculoskeletal model (Fig. 1) that represents the dynamics and control of human movement as a system of equations. While these equations are considerably more complex than the equations of projectile flight, the idea of representing a complex original system by a simpler model still holds.

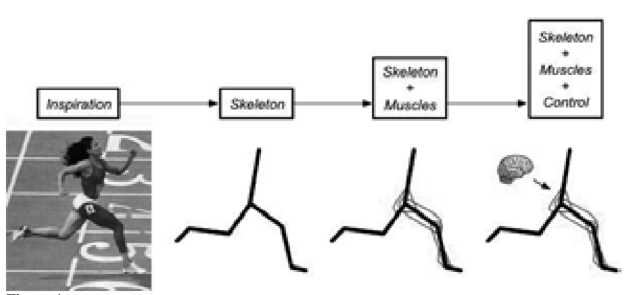

Figure 1.

Creating a musculoskeletal model involves defining equations that represent the human nervous, muscular, and skeletal systems to varying degrees of complexity (Fig. 1). In many studies cited in this review, the skeletal model was a system of rigid segments connected at joints, and the muscle models replicated classically observed input-output relationships between neural excitation and muscle force (e.g. Hill, 1938). The nervous system was not modeled explicitly but was assumed to generate the excitation signals sent to the muscles. The equations that describe the model's dynamics (e.g. skeletal motion, muscle force production) are called the state equations. The variables input to the state equations (e.g. muscle excitations or joint torques) are called the control variables. The output movement patterns calculated by solving the state equations (e.g. joint and segment angles) are called the state variables. Parameters (e.g. muscle strengths, body segment lengths) affect the relationship between the control variables and the state variables.

Performing a simulation amounts to solving the state equations for a given set of control variables, thus producing the movement pattern (state variables) of the musculoskeletal model. One of the major strengths of computer modeling and simulation is its predictive nature: any arbitrary set of control variables can be input and the resulting motion of the model determined. However, a guess at the control variables is unlikely to produce a realistic simulation. To generate realistic and useful movement simulations, the appropriate input control variables are determined using a mathematical technique called optimization (Neptune, 1999; van Soest & Casius, 2003; Higginson et al., 2005). For example, to simulate running, Neptune et al. (2000a) optimized the magnitude and timing of input muscle excitation signals to minimize the difference between simulated and experimentally measured running movements.

To simulate jumping, Anderson and Pandy (1999) optimized the muscle excitations to maximize the peak height of the jump. The optimization process is time consuming and can require days of computer processing time for complex models, even on powerful modern computing systems.

The approach used by Neptune et al. (2000a) to study running is known as "data tracking" because the goal is to replicate ("track") a measured human movement. The data tracking approach is attractive because it explicitly generates a realistic simulation if the model is sufficiently detailed. Variables that cannot be measured in humans (e.g. muscle forces) can then be extracted from the model and related to the observed human performance. The challenge of the tracking approach is to avoid over-fitting the model by using an unrealistically large or under-constrained set of control variables. In contrast to the tracking approach, Anderson and Pandy (1999) used a "predictive" approach to find the muscle excitations that maximized jump height. The simulation results were compared to data from humans performing the same movement, but the simulation was not tracking these data nor was it constrained to replicate them in any way. The predictive approach is attractive because experimental data from human subjects are not strictly required to generate the simulation. Optimal performances can therefore be predicted and then compared to actual performances from human subjects. The challenge of the predictive approach is to define an appropriate criterion for optimal performance that generates a human-like movement.

JUMPING FOR HEIGHT

Jumping is a convenient movement to study with the predictive simulation approach because of its unambiguous optimality criterion: maximize the peak height. Once the feet leave the ground, the eventual peak height of the jump has already been determined by the vertical velocity at take-off. Some simulations of jumping have therefore maximized the vertical velocity at take-off rather than maximizing the peak height. The motivation for this choice is primarily the savings in computer processing time, since simulating only the ground contact phase requires less time than simulating both the ground contact and airborne phases.

M.F. Bobbert, a researcher at the Free University of Amsterdam, has spent much of his career studying human vertical jumping (Fig. 2). In one of the classic examples of simulations applied to sports science, Bobbert and van Soest (1994) investigated the effects of muscle strength on peak vertical jumping height. An initial simulation was performed to confirm that the model could jump in a realistic manner and to produce a set of optimal muscle excitation signals. Next, the model's muscle strength was increased by up to 20%, and the simulation was repeated with the same excitation signals. Surprisingly, increased strength alone actually reduced the jump height. Increased strength led to higher jumps only when the muscle excitations were re-optimized to find a new set of optimal excitation patterns associated with the stronger muscles. The results indicated that adjustments in neuromuscular coordination were needed to take advantage of increased strength. The authors concluded that strength training should be accompanied by technique practice in order to optimally improve jumping ability.

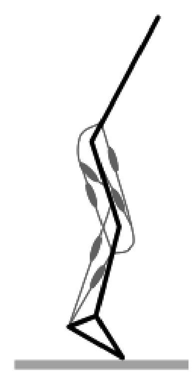

Figure 2.

In other virtual strength training studies, Cheng (2008) found that knee and ankle strength were more important than hip and shoulder strength for increasing jump height. Nagano and Gerritsen (2001) found that peak jump height was most sensitive to the strength of the knee extensor muscles (vasti). Muscle maximum shortening velocity and capacity for maximal muscle activation also substantially affected peak jump height. Experiments on human motor units and muscle fibers indicate that exercise training can alter both of these parameters (Fitts & Widrick, 1996; Gabriel et al., 2006), although it has been suggested that maximum shortening velocity is primarily affected by endurance rather than resistance training (Malisoux et al., 2007). Jump height was maximally increased when all three parameters (strength, maximum shortening velocity, maximum activation) were increased. The jumping studies cited so far were all simulations of squat jumping, where the model began from a static squatted posture. Humans can achieve greater peak heights when performing counter-movement jumps initiated from a more erect standing posture, with a downward movement prior to the explosive upward push-off. Bobbert et al. (1996) used their simulation model to investigate why counter-movement jump height exceeds squat jump height. Contrary to previous theories, the storage and return of elastic strain energy in muscles is not the primary reason for increased jump height with a prior counter-movement (van Ingen Schenau et al., 1997). Rather, the presence of the counter-movement allows time for muscles to build up higher activation and force levels prior to the push-off movement.

The peak simulated squat jump height is sensitive to the initial depth of the squat, at least when the model is constrained to not translate horizontally (Selbie & Caldwell, 1996). Domire and Challis (2007) and Bobbert et al. (2008) both found that a deeper initial squat produced a greater peak jump height, up to 13 cm higher than jumps from more shallow squats. Interestingly, the human subjects in Domire and Challis (2007) showed no relationship between squat depth and jump height, while the subjects in Bobbert et al. (2008) showed a relationship similar to the simulations: greater squat depths produced greater jump heights. Subjects in Domire and Challis (2007) were untrained, and the authors suggested that the deep squat jumps were unfamiliar motor skills for these subjects. In contrast, subjects in Bobbert et al. (2008) were trained gymnasts. These results as a whole further support the important role for technique practice in training for the vertical jump.

JUMPING FOR DISTANCE

From a simulation perspective, jumping for distance is conceptually similar to jumping for height, except the goal is to maximize displacement horizontally rather than vertically. In one of the few examples where modeling and simulation were applied to improve the performance of an individual athlete, Hatze (1981, 1983) developed a full-body musculoskeletal model and simulated the push-off phase of a long jump (Fig. 3).

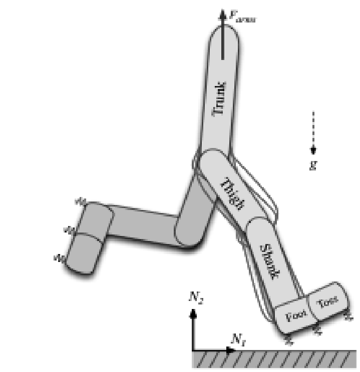

Figure 3.

The initial posture of the jumper on ground contact with the take-off board and the muscle excitation signals throughout the jump were optimized to maximize the horizontal displacement of the model's center of mass. The model's body segmental and muscular parameters were all derived from direct or indirect measurements of a 24-year old competitive athlete with an average long-jump performance of 6.58 m and a personal-best performance of 6.96 m. The athlete's performance was filmed and compared to the optimal performance predicted by the simulation. The model jumped further than the athlete, owing primarily to a greater angular range of hip extension and an earlier onset of hip extension during push-off. After three weeks of focused training on this technique adjustment, the athlete's average performance improved to 7.12 m.

In the same vein of predicting optimal long-jumping technique, Ecker's (1971) physics-based model predicted that athletes could greatly increase jumping distance by performing a forward somersault during the flight phase. The somersault technique exploits the angular momentum generated about the athlete's center of mass during the push-off, rather than fighting against it by extending the legs as in the hitch-kick or hang techniques. Somersault jumping gained some popularity in the 1970s when an early adopter reportedly improved his long jump by more than a foot (Reid, 1974), but was eventually banned by track and field's governing bodies when its competition performances began to approach those of the traditional techniques (Hay, 1993).

Hatze's (1981) model, although now 30 years old, is one of the most complex and detailed musculoskeletal models in the literature. Other researchers have used much simpler models to study long jumping technique. Alexander (1990) used a simple model with a point mass at the hips, a two-segment leg, and a knee extensor muscle to investigate optimal initial push-off kinematics (approach velocity and shank angle) that maximized long jumping distance. Despite the model's simplicity, the optimal kinematics (10 m s-1 and 60) agreed well with data from actual athletes. The optimal speed and shank angle were insensitive to parameters that defined the strength and power of the knee muscle, suggesting a general optimal push-off technique (assuming the athlete can reach 10 m s-1, which is quite fast). Chow and Hay (2005) used a similar simple model to investigate the sensitivity of jump distance to approach velocity and leg strength. When the parameters were changed in isolation, a 10% increase in approach velocity produced a 10% increase in jump distance, and a 10% increase in leg strength produced a 7% increase in jump distance. However, when both approach velocity and leg strength were increased by 10%, the jump distance increased by 20%. The results suggest that in long jumping, the whole is greater than the sum of the parts concerning speed and strength, and that both parameters should be trained simultaneously to optimize long jumping performance.

SPRINT RUNNING

Sprinting, like jumping for height or distance, presents a relatively unambiguous optimality criterion: maximize speed, or equivalently, minimize the time taken to cover the sprinted distance. Simulations of sprinting (and of running in general) are few in number compared to simulations of jumping, and the determination of optimal motions and muscle excitation strategies remains a relatively new frontier in modeling and simulation.

Researchers at the University of Wisconsin's Neuromuscular Biomechanics Lab performed a series of sprinting simulations using a three-dimensional (3D) full-body model (Thelen et al., 2005; Chumanov et al., 2007, 2011). Their focus was to identify periods of the stride cycle when hamstring strain injuries are most likely to occur. The model's joint torques were optimized to track kinematic data measured from athletes during high-speed treadmill sprinting. The torques were then distributed into individual muscle forces using so-called static optimization (Thelen et al., 2003). Analyses of muscle actions suggested that the hamstrings are most susceptible to strain injuries late in swing phase, when peak hamstring muscle fiber strains occurred while preparing the leg for ground contact. Sensitivity analyses indicated that increasing hamstring tendon compliance and strengthening the lumbo-pelvic muscles could reduce the potential for hamstring strain injuries.

In simulations performed by the authors, the muscle excitations of a 2D model (Fig. 3) were optimized to maximize the model's average horizontal speed (Miller et al., 2011). Muscular parameters were derived from joint strength tests on a group of athletic adult females. Although no measured data were tracked, the simulation compared reasonably well to joint angles and ground contact forces measured from the female runners (Fig. 4). Repeated simulations with various muscular properties removed suggested that the ability to generate muscle forces at a wide range of muscle velocities (i.e. power) is more important for sprinting than the ability to generate forces at a wide range of lengths (i.e. flexibility). However, large increases in muscle strength were needed for the model to achieve world-class speeds.

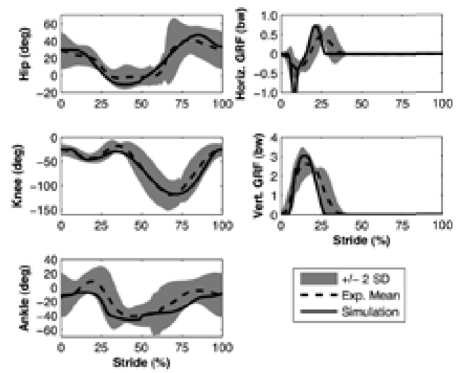

Figure 4.

Due to the identified importance of muscle power (force / velocity), additional simulations were subsequently performed to determine the sensitivity of sprinting speed to specific parameters that define the muscle force-velocity relationship. Speed was most sensitive to the amount of force that muscles could produce at moderate shortening velocities (Fig. 5),

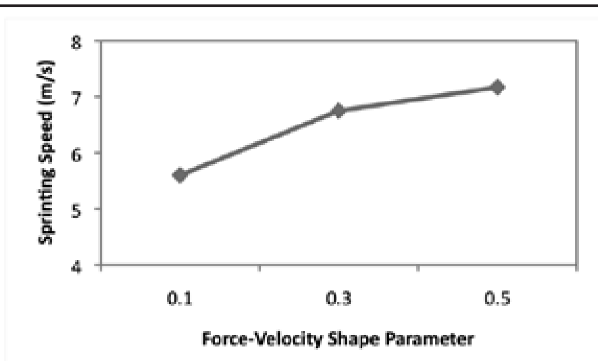

Figure 5.

which is primarily a function of the fast-twitch/slow-twitch muscle fiber ratios. While training status and type of exercise can have a small effect on the relative proportions of fast- and slow-twitch fibers, the proportion of fast glycolytic (type 2B) fibers appears to be largely genetic. The results therefore suggest a muscle mechanics-based explanation for why athletes with relatively high proportions of fast-twitch fibers may be predisposed to be good sprinters.

The sprinting studies noted so far all simulated the steady-state phase of the sprint, where the athlete has reached and attempts to maintain their maximum speed. Of equal importance is the acceleration phase, where the athlete attempts to accelerate out of the starting blocks up to their maximum speed as quickly as possible. Lee and Piazza (2009) used a model of the foot and ankle to simulate the initial push-off phase out of the starting block. Decreasing the moment arm length between the Achilles tendon and the ankle joint center increased the initial speed out of the blocks by allowed the calf muscle fibers to shorten at slower velocities. Lengthening the model's toes also increased the speed by prolonging the duration of ground contact and allowing more time to generate large propulsive forces. These findings were consistent with anthropometric measurements on competitive sprinters, who had shorter Achilles tendon moment arms and longer toes than size-matched non-sprinters.

ENDURANCE RUNNING

Simulating endurance running is a challenging task because the movement does not have an immediately intuitive optimality criterion. An athlete running a mile or a marathon is not absolutely maximizing speed (else they would sprint), nor are they absolutely minimizing the metabolic cost (else they would walk). In a race, the task objectives for endurance and sprint running are similar (cover the distance in minimum time), but the endurance runner cannot absolutely maximize speed without exhausting their metabolic energy stores well before the finish line.

Wright et al. (1998) and Neptune et al. (2000a,b) avoided the optimality criterion issue by performing data tracking simulations. The muscle excitations were optimized to track the joint angles and ground contact forces measured from running humans during the stance phase. However, to avoid overestimating muscle forces and antagonistic co-activation, the permitted timings of muscle excitations were constrained to be similar to EMG signals from the same runners. The three studies focused on estimating the internal muscular and joint contact forces during running and their implications for injury. Wright et al. (1998) performed tracking simulations of the impact phase (first 40 ms of ground contact) with the model of the foot-ground interface adjusted to represent either hard or soft running shoes. In agreement with data from humans running in different shoes, the magnitude of the peak external ground contact force during the impact phase was the same in both shoes, but the rate of loading increased in the harder shoe. Peak muscle forces were also sensitive to shoe type even though peak ground contact forces were not. Miller and Hamill (2009) reached a similar conclusion from tracking simulations with three different shoe cushioning levels. The magnitude of bone contact forces on the distal tibia increased with increasing shoe stiffness, even though the peak ground contact force was relatively unaffected. These studies illustrate that changes in external loading do not necessarily reflect internal musculoskeletal loading.

Neptune et al. (2000a,b) used the model of Wright et al. (1998) to simulate the entire stance phase. The first study (Neptune et al., 2000a) predicted the peak compressive joint forces near mid-stance to be 8, 12, and 9 times body weight for the hip, knee, and ankle, respectively. The second study (Neptune et al., 2000b) examined the sensitivity of predicted patellofemoral joint contact forces to commonly prescribed clinical interventions for patellofemoral pain: strength training and shoe orthotic inserts (Cutbill et al., 1997). Adding medially-wedged orthotics to the foot-ground contact model, increasing the strength of the vastus medialis muscle, or advancing the timing of vastus medialis excitation compared to vastus lateralis all decreased the peak and average lateral patellofemoral contact force. Vastus medialis strengthening consistently reduced the peak joint contact force in nine subject-specific simulations, while the effect of the orthotic intervention varied between subjects and did not always reduce the peak contact force. An additive effect was noted when all three interventions were included in the model simultaneously. The results provide biomechanical support for clinical practices in treating a common running injury. They also motivate the strength training of vastus medialis for avoiding patellofemoral pain, although it may be difficult in practice to strengthen this single muscle

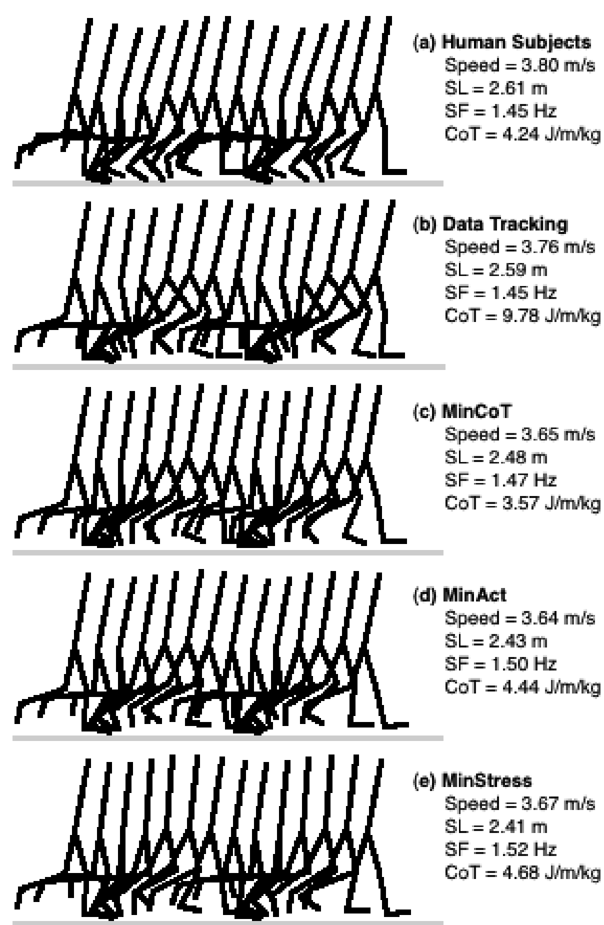

Figure 6.

in isolation.

Data tracking simulations such as Neptune et al. (2000b) are useful for estimating the internal loading of the body, but compromise some of the predictive nature of simulations by requiring measured experimental data to generate the simulation. Predictive simulations of running are challenging, as noted before, because of the lack of an intuitive optimality criterion. It has been suggested humans perform movements in ways that minimize the metabolic cost (Sparrow & Newell, 1998). Measurements of metabolic energy consumed by humans while running under various conditions have offered two general conclusions:

(1) The metabolic cost (energy consumed per distance traveled) is relatively insensitive to running speed (Margaria et al., 1963), although there are conflicting reports on the specific mathematical relationship between running speed and metabolic cost (Mayhew, 1977; Steudel-Numbers and Wall-Scheffler, 2009).

(2) When running at a given speed, humans naturally select a stride length that minimizes (Cavanagh & Williams, 1982; Hamill et al., 1995) or very nearly minimizes (Morgan et al., 1994; Gutmann et al., 2006) the metabolic cost.

These conclusions suggest that running does not have a well-defined, energetically-optimal speed, but that stride length at any particular speed is governed by a dynamic that maintains a low metabolic cost. Based on these findings, the authors used the model in Fig. 5 to generate predictive simulations of endurance running (speed = 3.6-3.8 m s-1) by minimizing several different criteria related to the metabolic cost: the metabolic cost itself, the level of muscle activation, or the level of muscle stress. The simulated running motions and salient descriptive data are compared in Fig. 6. Minimizing muscle activations, which avoids heavily taxing any one muscle regardless of its size or strength, predicted the most realistic metabolic cost in comparison to measurements from running humans (4.44 vs. 4.24 J m-1 kg-1; simulation 5% higher). Minimizing the metabolic cost itself, which preferentially avoids using the largest, strongest muscles that consume more energy than smaller muscles, predicted the least realistic metabolic cost, and substantially under-predicted the measured value (3.57 vs. 4.24 J m-1 kg-1; simulation 16% lower). The simulations suggest that runners adopt a muscle coordination strategy that avoids exhausting any one single muscle rather than one that absolutely minimizes the rate of metabolic energy consumption. Interestingly, the predictive simulations selected shorter stride lengths than the human subjects, regardless of which quantity was minimized. Runners who do not naturally use their energetically optimal stride length tend to over-stride (Morgan et al., 1994). The simulations therefore support the notion that runners may gain an energetic benefit by slightly reducing their stride length.

CONCLUSIONS ON TRAINING AND CONDITIONING

This review highlighted some of the unique information on human running and jumping that can be obtained from computer simulations of these movements. To conclude, we will suggest how coaches and athletes can use this information in their training and conditioning programs to improve performance.

The Bobbert and van Soest (1994) vertical jumping simulation suggests that resistance-training programs for improving muscular strength should be accompanied by skill practice to take full advantage of any gains in strength. This conclusion likely generalizes to long jumping, sprinting, or any movement that requires a combination of strength and skill. The suggestion that athletes engage in training protocols that improve both strength and skill is somewhat obvious, but the simulations at least provide a physiological rationale for why this is necessary. Studies that assessed the sensitivity of jumping performance to the strength of specific joints and muscle groups reported that knee extensor strength was the most important variable (Nagano & Gerritsen, 2001; Cheng, 2008). However, the greatest increase in jump height consistently occurred when the overall strength of the legs (all muscles) was increased. Overall strength is likely beneficial for avoiding injuries related to muscular imbalances as well.

In addition to muscular strength, simulations have indicated that vertical jump height is highly sensitive to the muscle fiber maximum shortening velocity (Nagano & Gerritsen, 2001; Domire & Challis, 2010). The maximum shortening velocity in human muscle fibers does not change much with resistance training, but is increased by endurance training (Fitts & Widrick, 1996; Malisoux et al., 2007). These results suggest that jumping athletes should include endurance exercise in the training programs, even if their competitive event performance does not depend directly on cardiovascular endurance.

The sprinting simulations of Chumanov et al. (2007) found that small perturbations to forces produced by lumbo-pelvic muscles during sprinting induced large increases in the peak hamstring strain. The simulation results suggest a novel and nonintuitive mechanism for hamstring strain injuries. It is difficult to infer suggestions on injury prevention and rehabilitation from this result, as it is not immediately clear how adjusting the lumbo-pelvic muscular properties would affect this sensitivity. However, since a stronger muscle can respond to an absolute perturbation level with a smaller increment in activation than a weaker muscle, it seems reasonable to suggest that strengthening the lumbo-pelvic muscles would be beneficial for preventing hamstring strain injuries.

Regarding optimal and observed sprinting techniques, our sprinting simulation (Fig. 4) ran at 6.8 m s-1 while the subjects upon whom the model's parameters were based had an average maximum sprinting speed of 6.5 m s-1. The simulation spent less time in contact with the ground (28% of the stride) than the human sprinters (37% on average). The 12 human subjects were all fit and athletically active, but only one had any formal coaching in sprinting technique. Although we did not assess the effects of technique adjustments based on the simulation results as Hatze (1983) did, the short ground contact time in the speed-maximizing simulation is consistent with the "paw the ground" advice often used to coach competitive sprinters.

Predictive simulation of human endurance running is a relatively new area in computer modeling and simulation. Our assessment of the running motions generated by minimizing various criteria (Fig. 6) was driven primarily by scientific interest regarding what criteria the nervous system prioritizes when activating the muscles for running. However, the results did support the idea that some runners may gain an energetic benefit by slightly shortening their stride length (Morgan et al., 1994). Shorter strides could also be beneficial for reducing the risk of tibial stress fractures (Edwards et al., 2009). However, many runners naturally select an energetically optimal stride length when running at any particular speed (Gutmann et al., 2006), so the suggestion of adopting a shorter-than-preferred stride length may not generalize to all runners.

One of the greatest strengths of computer simulation is the ability to expose a virtual athlete (the model) to conditions that would be impossible or unacceptable for an actual athlete. Most coaches would be unwilling to submit their athletes to an experimental protocol akin to Bobbert and van Soest (1994), in which half of the athletes would not practice at all for an extended period. Most athletes would be hesitant to participate in an in vivo version of Pandy and Zajac (1991), where gastrocnemius was changed from a two-joint muscle to a one-joint muscle. It is almost impossible to strengthen or change the force-velocity properties of an individual muscle in isolation. Yet a computer model will not object to these treatments, their effects are fully reversible, and researchers can gain insights that cannot be achieved in any human experiments.

In conclusion, simulations of human running and jumping have been tremendously useful in research environments for assessing variables that cannot be measured on live human athletes, for predicting optimal techniques by which to perform these movements, and for inferring relationships between muscular properties and movement performance. However, simulations have yet to become a common tool in coaching and athletic training. The long-jumping study described by Hatze (1983) is a rare example of a computer simulation used to directly and successfully improve athletic performance. The study was published 28 years ago, and the authors are not aware of any similar publications in the track and field literature, although simulations have been used as training aids for athletes in aerial sports such as gymnastics (Yeadon, 2008). Computer simulations have been promoted as tools for predicting clinical orthopedic and sports training outcomes since their inception in human movement science (Chow & Jacobson, 1971; Ghosh & Boykin, 1976; Hatze, 1976). The contemporary lack of this application despite strong evidence of its utility is likely due to the time required to develop and perform simulations; indeed, Hatze (1976) noted that 2300 man-hours were required to generate a subject-specific kicking simulation. However, with modern advances in high-performance computing (e.g. Anderson et al., 1995) and user-friendly simulation software (e.g. Delp et al., 2007), the raw time investment required for simulations is diminishing. An expanded role for simulations in the training of athletes will require closer collaborations between coaches, athletes, and researchers and greater efforts by researchers to promote the practical utility of simulations that are currently confined mostly to research labs.

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