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Opinion Paper

Perspective: A head-to-toe view on athletic locomotion with an emphasis on assessing core stability

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A R T I C L E I N F O

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A B S T R A C T

Although much research has been devoted to gait analysis while walking or running, a surprising gap in knowledge is its relationship with upper body function, particularly core stability. The methods used to train and assess athletic locomotion are mainly focused on the lower limbs, while the upper body is often overlooked. Yet, proper body alignment from feet to head is essential for applying maximum force to the ground, thereby moving faster and more efficiently. It is believed that the core, which connects the upper and lower body, should be strong. The training of many athletes is therefore aimed at developing core muscle strength. However, for most of them, rigid core musculature associated with reduced spinal mobility may not be beneficial. Instead, core strength should be developed to the extent that allows race walkers and runners to optimize their performance. Accordingly, methods reflecting the functional nature of core strength, along with measures of postural alignment and lateral lumbopelvic stability, should be used to assess training effectiveness. To this end, a comprehensive head-to-toe approach to the assessment of athletic locomotion is recommended. Special emphasis should be placed on the role of postural and core stability in walking and running gait.

1. Introduction

Locomotion is a complex human behavior that includes repetitive movements such as walking, running, sprinting, skipping, hopping, jumping, leaping, galloping, side-stepping, and swimming. Among them, much research so far has focused on walking and running analysis.

Walking mainly involves the muscles of the lower body (quadriceps, hamstrings, gluteals, adductors and calves). The upper body supports the trunk and stabilizes the pelvis to keep the body upright while walking. In particular, the erector spinae and abdominal muscles help stabilize and control the movement of the trunk. Arm muscles are less involved in the work when walking. Their main function is counterbalancing the lower limbs. Arm swing and a moderate step width reduce energetic costs and contribute to maintaining lateral balance.[1]

When running, similar muscles (quadriceps, hamstrings, gluteals, hip flexors and calf muscles) are activated, but to a different extent depending on whether it is a straight-line or change of direction (COD) run. The core is more activated during sprinting as hip extension increases with each stride to generate speed. Natural arm swing and narrow stride width improve lateral balance while minimizing energy costs.[1]

The core is considered "the engine" of upper and lower limb movements. It has a significant impact on the athlete's ability to generate and transfer forces to the limbs.[2] While core strength is related to the strength of the trunk muscles, core stability is defined as the ability to control trunk movements over the pelvis and lower limbs in order to provide conditions for optimal force transfer throughout the kinetic chain to the terminal segment.[3] This makes it clear that core stability plays a key role in optimizing an athlete's locomotor performance and preventing injuries.[4,5] As interesting as it may be, greater core muscle strength is unlikely to improve athletic locomotion. Instead, better neuromuscular control of the core musculature contributes to more efficient sport-specific functional movements.[6]

However, the association of kinetic and kinematic gait variables with those of core stability and strength has still received little attention. A variety of platforms and wearable sensors are commonly used to assess athletic locomotion. Relevant data can be obtained by pressure mapping combined with inertial measuring units. Especially frequently used foot-mounted inertial measurement units enable the monitoring of biomechanically relevant spatio-temporal parameters in sports field conditions.[7] However, most of these methods focus on the motion of lower

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Abbreviations

COD	Change of Direction
CoM	Center of Mass
CoP	Center of Pressure
GRF	Ground Reaction Forces
ROM	Range of Motion

limbs, whilst the influence of the upper body is often neglected. In particular, the assessment of core muscle strength and stability in relation to locomotion is often overlooked.

In sports, core muscle strength is usually measured by how much weight is lifted and how many repetitions are performed. Core muscle endurance is measured by how long an individual is able to maintain a neutral, stable position. In this way, for example, a 35 m sprint time was found to be significantly correlated with prone bridge performance,[8] meaning that subjects with better core endurance have better short-distance running times. In the laboratory, isometric and isokinetic dynamometers are often used to measure core muscle strength.[9] Another alternative is to assess core muscle strength during lifting tasks[10] or trunk rotations.[11] Core stability is more difficult to assess than core strength because it requires the incorporation of coordination and balance. Due to the complex interaction of the lumbo-pelvic-hip structures, there is no single test suitable for assessing core stability. Furthermore, adaptations in core stability after sport-specific training can only be revealed using tests designed according to the specific requirements of the given sport.[12]

However, the current approach typically focuses on the biomechanical analysis of specific phases of walking or running and the corresponding muscle activity, lacking information from the core region. This is despite the fact that the importance of the lumbo-pelvic-lumbar complex in locomotion is generally recognized. Yet, postural and core stability have not been adequately linked to walking and running mechanics. Is it possible that currently used generic tests may fail to assess core stability during walking, sprinting, or running? Although many of them assess core strength and stability, less is known about the extent to which their variables are related to walking and running speed. The question, therefore, is whether current assessment methods fully capture the role of core stability in locomotion. This work highlights the need for a systematic head-to-toe approach to assessing athletic locomotion, considering the important role of postural and core stability in walking and running performance.

2. On importance of lumbopelvic stability for athletic locomotion

The body is aligned along a vertical line, starting from the feet up to the head. The main function of the head, arms, and trunk is to counterbalance the angular motion around the three anatomical axes of the lower limbs during running.[1,13–15] Understanding the interaction between individual parts of the human body is important when assessing walking and running gait. A problem affecting one part of the body can lead to deterioration elsewhere. Any gait deformity is then compensated for by another part of the body. Or conversely, postural abnormalities may contribute to abnormal gait.[16] Addressing the underlying causes of athlete gait and posture abnormalities is therefore essential for improving their locomotor performance. In particular, lack of sufficient coordination in the core musculature can lead to less efficient movements, compensatory movement patterns, strain, overuse and injuries.[17–21] For instance, an increase in anterior pelvic tilt during sprinting would potentially predispose soccer players to hamstring injuries.[22,23]

It is well known that the amount of force applied to the ground is detrimental to maximal running speed.[24] At the moment of ground loading, the head should be aligned directly over the foot to apply maximum force.[25] Maintaining lateral postural stability without moving the head from side to side is essential for effective walking and running.[26] The exception is the start of the sprint, where the head is forward of the feet and side-to-side movements are greatest.[27]

In addition to the head, it is also important to consider the function of the arms' movement, which counteract the moments of the swinging legs around the vertical axis.[28] The swing of the arms during race walking is accompanied by a transverse rotation of the thorax in an opposite direction to the pelvis, with the rotation of the thorax about twice that of normal walking.[29,30] The range of pelvis rotation around the vertical axis is also greater during race than normal walking.[31] Large transverse plane movements during race walking create torsion in the trunk.[30]

It is therefore obvious that the pelvic and hip musculature plays an essential role in transmitting forces to the lower limb and the function of the foot. Good lumbopelvic and proximal stability is particularly important for efficient lower limb movements and distal mobility.[32,33] Lumbopelvic stability is closely associated with proper postural alignment.[34] The core stabilizes the spine and provides support to the kinetic chain during functional movements. It enables optimal force production and transmission to the end segment within integrated kinetic chain activities.[3] This ability to control the position and motion of the trunk over the pelvis and leg is known as core stability.

3. The trade-off between a rigid and stable core and spinal mobility

Core stability is often interpreted as having a stable core of the body. In the light of this, a too stiff core could be a disadvantage for walkers and runners. However, it depends on the trunk range of motion (ROM). Limited trunk rotation in the transverse plane during walking increases stride rate.[35] Similarly, restricted dorso-lumbar motion significantly reduces total gait stride and swing time, suggesting a shift to shorter and thus more frequent steps when running.[36] Such an increased stride rate can be beneficial for an athlete's performance. On the one hand, runners may be able to utilize elastic energy more efficiently by increasing stride rate, which may lead to a more economical running style, but on the other hand, restricted trunk rotation may be detrimental to running economy.[37]

This can be attributed to less vertical movement of the center of mass (CoM) during the casted running.[38] Reduced spinal mobility increases ankle shear stress and ground reaction forces (GRF) at heel strike, while decreasing GRF at toe-off.[39] Such a decrease in spinal mobility could probably contribute to a shorter stride length and greater muscle activity of erector spinae muscles and quadriceps.[36] Conversely, a positive correlation between the degree of spinal rotation and stride length while jogging means that greater spinal rotation results in a larger stride.[40] Although there were trends suggesting that increased spinal rotation led to reduced compressive joint forces at the knee, it was not demonstrated to decrease GRF during the gait cycle.[40]

On the other hand, stride length is longer and stride rate is lower when running with exaggerated rather than natural and restricted trunk rotation.[41] However, purposely increasing trunk rotation during running does not alter the overall running kinematics, such as the speed and ROM of the hip, knee, and ankle joints during braking and propulsive phases.[41] This can be a case of fast running, during which the trunk ROM around three axes increases.[42] This observation is supported by later research reporting a strong correlation between 40 m sprint time and isometric back extension strength measured using the Biering-Sørensen test in tennis players.[43] This parameter is also significantly correlated with lateral flexion and abdominal flexion strength, and isometric back extension and lateral flexion endurance in tennis players,[43] lateral flexion strength in netball players and runners,[43] and core neuromuscular control assessed using a pressure biofeedback unit in soccer players.[43] The predictor of sprinting seems to be only lateral flexion strength, meaning that its higher values lead to lower sprint times.[43]

However, a strong foundation of muscular balance and a stable core is important for middle- and long-distance runs that require powerful body movements.[18] Especially long-distance runners can benefit from increased trunk stabilization, which contributes to faster running speeds. The angular impulse of the arms and trunk around the vertical axis helps alternate both legs during the non-contact phase of running.[13] The swing of the arms is coordinated with the trunk to balance the angular momentum of the leg movements during running.[13]

The results in the previous paragraphs suggest that core muscle strength, core stability, and spinal mobility should work together for effective locomotor movement. Locomotion requires a certain amount of flexibility to adapt to different speeds, turns, or obstacle avoidance, and therefore must deal with a certain level of non-linearity.[44] However, the extent to which strong and stable core and spinal mobility contribute to locomotor control warrants further investigation.

4. Is core stability related to walking and linear running speed?

Locomotor performance requires neuromuscular control of the whole body rather than high muscle strength. Trunk muscles, both the local and global stabilization systems, must work coherently to achieve core stability.[45] While the smaller trunk muscles of the local stabilization system play a major role in coordinating and controlling movement segments, the larger trunk muscles of the global stabilization system provide more forceful movements.[46] Their appropriate muscle recruitment and timing are very important for the execution of the movement.[45] The activity of trunk muscles is clearly related to lower limb movement.[19] Specifically, there is a link between trunk muscle activity that precedes limb prime mover activity and hip movement (anticipatory responses).[32] The central nervous system provides a basis for limb movement through the co-contraction of particular muscles.[45] It stabilizes the spine by contracting the abdominal and multifidus muscles in anticipation of reactive forces generated by limb movement.[32] However, only a small increase in the activation of abdominal muscles (about 10% of maximal voluntary contraction for rigorous physical activities) is needed to stiffen the spinal segments.[3] This indicates that sensorimotor control is much more important than the strength and endurance of the trunk muscles to provide sufficient core stability.[45]

In closing, the answer to the question posed in the heading of this section is that better overall neuromuscular coordination, rather than core stability alone, contributes to higher walking and linear running speeds. However, how large this contribution requires further investigation. Examining specific groups of elite race walkers and sprinters may reveal unique relationships between key variables. Wearable sensors can provide useful information about the movement of individual body parts in relation to locomotor performance. For one, such measurements can be easily used in the sports field; and second, it has ecological validity for testing athletes' performance in real-world settings.

5. Is core stability related to change of direction speed?

In addition to straight-line running, core stability plays an even more important role when running with COD, which consists of the full spectrum of turns. This requires reducing horizontal momentum, rotating the body, and placing the foot in front of the CoM to produce a horizontal braking and propulsive impulse, followed by re-acceleration in the desired direction of motion.[47–49] Thus, effective turning performance involves greater penultimate foot contact with hip and knee flexion accompanied by lowered CoM, increased horizontal braking forces over shorter ground contact times, increased trunk tilt, and pelvic and foot internal rotation.[49–55] It is obvious that higher medio-lateral ground reaction impulses are accompanied by greater medio-lateral CoM – CoP (center of pressure) trajectories.[52] Athletes try to adjust their CoM-CoP trajectories by higher lateral foot plantar distances and trunk tilt in the desired direction to produce medio-lateral force and impulse. This, among others, depends on the range of pelvic rotation, which is greater during larger than smaller angled cuts, i.e. during 110° than 45° cuts[53] and 90° than 45° cuts.[54] The hips act as a stabilizer during 90° cuts because the hip adductor moments are higher and the anterior and transverse force production is relatively low.[54] On the other hand, the hips contribute to propulsion during 45° cuts due to the higher production of sagittal and transverse hip forces and the transition from hip adduction to hip abduction moments during stance.[54] Faster changes in the direction of movements by 75° are associated with a greater lateral rotation of the thorax,[55] suggesting that redirection in sharper angled cuts is achieved by whole-body rotation and trunk tilt rather than just the lower limbs.

It is therefore clear that, in addition to the strength and speed of leg muscles, core strength is also among the physical factors contributing to agility performance in invasion sports.[56] This is the case with many COD speed and agility tests. A recent review revealed a significant association of agility T-test time with stability and/or strength of the core muscles but not with their endurance.[57] Specifically, significant correlations were found between agility T-test time and isometric back extension and abdominal flexion strength in tennis players,[43] lateral flexion and abdominal flexion strength in hockey players,[43] lateral flexion strength in netball players,[43] core neuromuscular control, and isometric back extension and abdominal flexion strength in soccer players,[43] lateral flexion endurance, and lateral flexion and abdominal flexion strength in runners,[43] and core stability measured using stabilizer pressure biofeedback.[58] Additionally, pro-agility test and 40-yard dash times were correlated with the distance of reverse and lateral medicine ball throws in football players.[2] However, weak, non-significant correlations were reported between the T-test and 40-yd dash times and abdominal strength in collegiate athletes.[59] Furthermore, time in the Hexagonal obstacle test was found to be associated with postural stability but not with core muscle endurance in basketball players.[60] On the contrary, time in the pro-agility shuttle run, and 20- and 40-yard sprints were significantly correlated with the holding time during McGill torso endurance tests[61] such as back extension, trunk flexion, and lateral bridge in football players.[62] Similarly, significant correlations were found between holding time in the prone plank test and time in the 30 m sprint and step 50 agility tests, as well as time in the Yo-Yo intermittent recovery test and Cooper test in soccer players.[63] In particular, movement capacity is related to core stability in physically active adults.[64]

Inconsistent results found in these studies may be due to gait parameters used for data analysis (e.g., stride length, stride rate, etc.) being influenced by other factors from the proximal end of the body segment (i.e., trunk).[65] This includes directions of movement (triplane activity) and core specific functions (trunk control over the planted leg).[3] Therefore, in addition to traditional biomechanical analysis of walking and running technique, ongoing and future work should involve targeted assessment of specific abilities and skills crucial for locomotion. Since sacrolumbar spine position has been found to be positively related to agility T-test time and 20 m linear speed,[66] measurements of spinal curvature may also provide valuable information in predicting speed and COD abilities.

Although most current tests provide valuable information about core strength and stability,[67] they do not monitor core variables simultaneously with locomotion measures. In effect, the association of the core with race walking, sprinting, and long-distance running speed has not been fully explored, so it needs to be investigated more systematically using a more advanced approach to assessing athletic locomotion.

6. Summary points

i) Proper body alignment along a vertical line from the feet to the head is essential for applying maximum force to the ground, thereby moving faster and more efficiently. This is especially true for effective walking and running. Until now, much research has been devoted to gait analysis while walking or running, whereas a surprising gap in knowledge is its relationship with upper body function. Methods used to train and assess athletic locomotion have also focused mainly on the lower limbs, with the upper body often neglected.

ii) Although the core represents the center of the body connecting its upper and lower parts, the role of core stability in walking and running has received very little attention so far. In particular, the amount of force produced by the core muscles during walking or running, which is usually associated with the range of trunk rotational motion, remains an open question.

iii) Evidence supports the use of core exercises to increase the strength of the trunk muscles of athletes, but it is noteworthy that for most of them, strong and rigid core musculature associated with reduced spinal mobility may not be beneficial. Instead, core strength should be developed to the extent that allows race walkers and runners to optimize their performance.

iv) Given this, methods that reflect the functional nature of core strength, along with measures of postural alignment and lateral lumbopelvic stability and mobility, need to be incorporated into the analysis of locomotor performance.

7. Future issues

i) It is believed that the core, which connects the upper and lower body, should be strong. The training of many athletes is therefore aimed at developing core muscle strength. However, from an athlete training standpoint, it is useful to take a step back and ask the question: How much trunk muscle strength is needed to perform effective human movements involving core musculature?

ii) The essential idea behind the contribution of core stability to an athlete's locomotor performance revolves around two simple approaches. The first should explore the relationship between core stability and/or core strength and various forms of human locomotion, especially walking and running. The second approach should address the relationship between core stability and/or core strength and sport-specific performance. Clearly, studies are needed to test the link between the two assumptions. First, to test the hypothesis that core stability is associated with relevant parameters of locomotion such as walking and running. If the hypothesis is rejected, an alternative question is to what extent core stability contributes to sport-specific performance that involves the use of core muscles.

iii) In addition, studies on the effects of core muscle training on locomotion variables as well as on athlete performance are also needed. Accordingly, methods reflecting the functional nature of core strength, along with measures of postural alignment and lateral lumbopelvic stability, should be used to assess training effectiveness.

iv) To this end, a head-to-toe assessment should include the systematic collection of data on all parts of the body relevant to walking and running gait. Starting with postural alignment, through core stability/core strength along with trunk rotational mobility up to walking and running movement, such an approach should provide a comprehensive insight in an athlete's locomotor performance.

Availability of data and materials

The data within this study are secondary data and available through the relevant sources referenced.

Declaration of competing interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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