THE IMPORTANCE OF ANALYSING LOWER LIMB MOVEMENT PATTERNS IN RACEWALKING

Mihaela ACATRINEI[1*]

[1] Craiova University, Faculty of Physical Education and Sport, Craiova, Romania
*Corresponding author: mihaela.acatrinei.ma@gmail.com

DOI: https://doi.org/10.51267/icehhm2024bp04

Abstract: *The walking test, as stipulated by the regulations, dictates that there should be no visible loss of contact with the ground, and the advancing foot must be extended from the moment of initial contact with the ground until the vertical position. This paper proposes a comprehensive review of the lower limb profile of racewalking athletes, outlined through an analysis of specialized literature, by conducting a narrative review analysis. The analysis of specialized literature included a total of 35 articles, based on keywords related to lower limb biomechanics in racewalking, movement patterns in racewalking, and muscular behaviour of the lower limb in racewalking. From the analysis conducted, we found that the hip flexors and extensors were the main generators of energy along with the plantar flexors, while the energy absorbed by the knee extensors counteracts the negative role of the knee flexors, thus reducing the risk of injuries by stabilizing the knee in extension. From a kinematic perspective, several studies have analysed the maximum medial/lateral rotation of the forefoot during the walking test, and the conclusion was that there are significantly increased values, which are an important aspect in monitoring the fatigue that can occur at this level. From a training perspective, achieving performance is supported by many authors based on the monitoring of certain measurable indices through systems that use accelerometers. These indices refer to measuring ground contact time, step length, and cadence. The biomechanics of the lower limb play a crucial role in racewalking performance, and understanding these principles can contribute to optimizing training and performance in this specific athletic event.*

Keywords: *lower limb; biomechanics; racewalk.*

Introduction

Race walking is one of the specific disciplines of athletics, born in Great Britain in the 16th century, which is dominated by the mechanics of movement, especially, pelvis and lower limbs. The rules for this sport, accepted by the International Association of Athletics Federations (IAAF), are very demanding for athletes because the emphasis is placed on biomechanical elements and coordination during the training (Skublewska-Paszkowska, et al. 2018).

Race walking is an Olympic event dictated by Rule 230.2 of the International Association of Athletics Federations (IAAF), according to which there must be no visible loss of contact with the ground, and "the advancing leg must be straightened (i.e., not bent at the knee) from the moment of first contact with the ground until the vertical upright position" (IAAF, 2015, p. 253). This strictly enforced rule affects the walking mechanics of the entire body (Hanley & Bissas, 2016), and the knee is, therefore, the most important joint to evaluate in terms of legal race walking technique (Hanley et al., 2018).

The term "vertical upright position" introduced by the IAAF (International Association of Athletics Federations) in 1972 refers to the specific moment during a race when the body's center of mass passes directly over the supporting leg (Figure 1). This is an essential concept in the biomechanics of race walking, used to evaluate the technique and efficiency of race walkers. For convenience, the moment when the body's center of mass passes over the supporting leg has been called "midstance." It is important to note that while this term is commonly used to designate a specific point in the biomechanics of race walking, it is also used to describe a phase of the walking cycle, not just a single moment.

It is important to note from the wording of the rule that the loss of contact with the ground is evaluated with the naked eye, which is not capable of detecting very short flight periods. For this reason, while measurements made with high-speed cameras or force plates might record short flight periods, this does not mean that an irregular movement has occurred (Hanley, 2014).

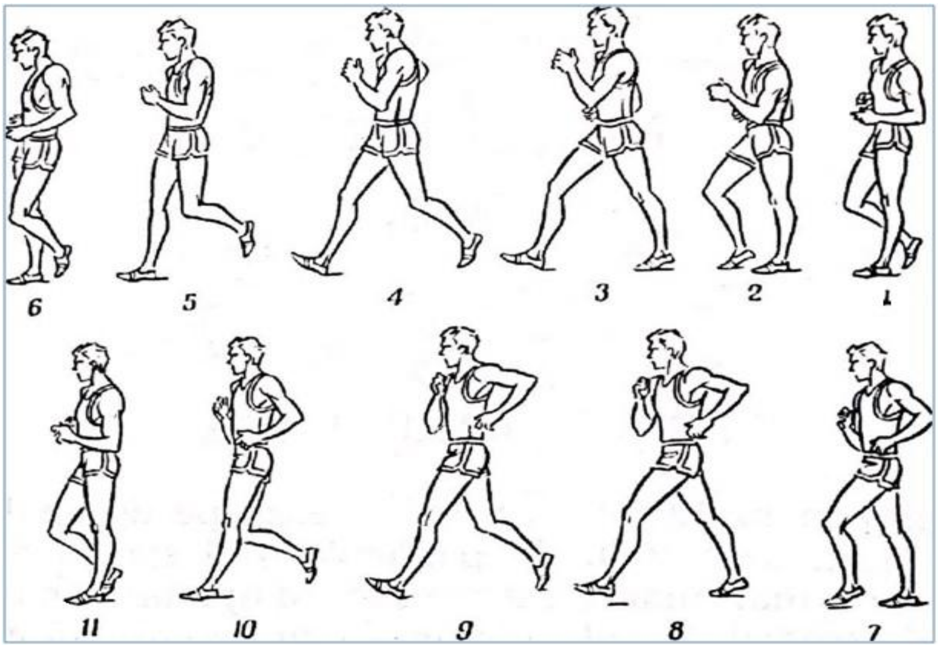

Figure 1. Race walking technique (Homenkov L.S, 1977, p. 580)

The swinging foot lifts slightly off the ground and continues the propulsion, achieving triple flexion simultaneously with the extension initiated in the knee joint. Upon reaching the necessary height, the thigh of the swinging lower limb begins to descend, and with it, triple extension occurs.

The first contact with the ground occurs on the heel, as close as possible to the median line of displacement. Then, the walker proceeds to roll through the entire sole, most often with a rolling motion on the outer edge of the foot.

The support phase concludes when the foot transitions from the entire sole to the toe. During the completion of this phase, the foot has not yet lost contact with the ground, while the other foot makes contact with the ground with the heel. (Homenkov, 1977)

At one moment, the athlete is in a position of bilateral support, with greater loading pressure on the foot about to make contact with the ground compared to the contralateral foot. (Homenkov, 1977)

Race walking is a form of locomotion that is not different from normal walking or running, but nevertheless, the rule that regulates it and competitors' attempts to move as fast as possible result in some noticeable differences. Generally, the initial contact is made on the lateral heel, with higher pressures on the outer side of the foot compared to normal walking (Villarroya et al., 2009). The knee is extended from the initial contact, whereas in normal walking, it flexes slightly (Levine et al., 2012). Exaggerated movements of the shoulder and pelvis tend to occur in race walking, giving it its distinctive appearance. The elbows are flexed at a smaller angle than a right angle, similar to those of a long-distance runner, and the shoulders move through a much greater range of motion than in normal walking (Hanley, 2014).

Race walkers must develop their performance parameters while refining their technique, so as to adhere to the rules and avoid disqualification. Understanding the basic biomechanical factors is particularly important for the precision of the technique required by the event's rules.

A comprehensive understanding of the role of major muscle groups in race walking is clearly important for developing appropriate training methods that consider the specific requirements of this unique form of competition. The role of mechanical movements in race walking has been described in previous studies (Cavagna & Franzetti, 1981), but may not apply to current athletes, considering that these studies were conducted in compliance with the rules before 1995, which did not require the knee to be straightened at the first contact with the ground. Additionally, although moment values for lower limb joints have been measured in race walking (Hanley & Bissas**,** 2013; Hoga et al., 2006), the crucial role of mechanical work has not been similarly reported. (Hanley & Bissas, 2016).

While muscle moment values provide insight into the forces acting on the joints during training, understanding the role of factors such as muscle contraction efficiency, force transfer through the skeletal system, and overall energy expenditure are necessary for achieving efficient performance in race walking.

In these circumstances, biomechanical analyses of the lower limb in race walking are necessary to better understand the biomechanical requirements and to develop potential training strategies aimed at optimizing performance and reducing the risk of injury in high-performance athletes.

Aim

Within this work, we propose a review of the biomechanical behavior of the lower limb in athletes practicing race walking, a behavior outlined through the analysis of specialized literature, allowing us to conduct a narrative review.

Material and method

The literature review included a total of 35 articles selected from databases such as Web of Science, PubMed, Google Scholar, and Medline. The selection was based on keywords related to biomechanics of the lower limb in race walking, movement patterns in race walking, and muscular behavior of the lower limb in race walking. Using these keywords, we found a total of 80 full-text articles, from which we excluded 45 articles that addressed biomechanics of the lower limb in other sports or in individuals with locomotor disorders. It is worth mentioning that the specialized literature did not include scientific sources, specifically targeting race walkers. The considered publications encompass new insights on race walking from a technical perspective. We only considered materials published in English that addressed biomechanical analyses of the lower limb.

The exclusion criteria for these studies were as follows: studies that did not have specific results for race walking, studies that did not present results on the kinematic parameters of the lower limb in race walking, and studies that did not present results about the biomechanics of the lower limb in race walking.

The elements considered were related to observed results regarding ground reaction force, kinematic parameters of the lower limb and muscle behavior using electromyography studies (EMG).

Results

In recent research, several studies (Cairns et al., 1986) have focused on describing the *kinematics of race walking* due to its unique characteristics and investigating the technical factors that can influence athletes' performance (Pavei & La Torre, 2015). This paper introduces a new motion analysis protocol specifically designed for race walking, which was tested on an athlete from the Italian national team under controlled laboratory conditions. Data analysis focused on evaluating knee flexion-extension and detecting moments of loss of ground contact (i.e., flight phase). Additionally, the study estimated push-off and strike angles, as well as the angles of the pelvis, hip, ankle, and elbow joints, along with the temporal components of gait to assess biomechanical efficiency. The results obtained are consistent with those in existing literature, despite differences in methods and experimental protocols. The developed motion analysis protocol enhances the understanding of race-walking techniques and could serve as a valuable tool for athletes in improving performance and for coaches in analyzing movement characteristics.

In the same context, we found studies that aimed to compare knee angle measurements recorded through 2D videography and 3D optoelectronic systems.

For this, Hanley and colleagues. (Hanley et al., 2018) applied reflective markers on the right foot of 12 racewalkers for the 3D systems, and recording was done at a frequency of 250 Hz, while 2D video data were simultaneously recorded at 100 Hz. Knee angles were initially calculated based on marker coordinates and separately using a 3D model. Video data analysis was conducted both through automatic tracking and manual digitization to create four different evaluation conditions.

The results highlighted minor differences between systems, but the 3D model indicated larger angles at midstance compared to using automated tracking and marker coordinates (by 3–6°, $P < 0.05$). These discrepancies could be attributed to how the 3D model locates the hip joint and the addition of marker clusters. Additionally, 2D videography provided similar results to the 3D model when manual digitization was used, allowing for the correction of errors caused by skin movement (Hanley et al., 2018).

Also, Hongzhao and colleagues (Hongzhao Wang et.al, 2016) in their study measured changes in maximum medial/lateral rotation of the forefoot in the horizontal plane during walking on a treadmill, using a fatigue protocol.

In their study, 11 young race walkers participated. To identify changes in maximum medial/lateral rotation of the forefoot, a wireless motion capture device with 8 channels (MVP-RF8-BC) was used. It was found that the maximum medial/lateral rotation of the forefoot in the horizontal plane was significantly associated with increasing pace during progressive walking on the treadmill. Additionally, significant increases in maximum medial/lateral rotation of the forefoot were observed during treadmill walking at speeds of 8 km/h and 10 km/h.

The conclusions of this study suggest that maximum medial/lateral rotation of the forefoot increases in a fatigued state, implying changes in the kinematic characteristics of the forefoot.

Ground reaction forces (GRF), through double integration, are also used to calculate the trajectory of the body's center of mass (BCoM) and describe the mechanics of movement (Cavagna, 1975). In race walking, the trajectory of BCoM can only be accurately calculated using a direct dynamic approach, whereas inverse dynamics calculation has proven to be biased (Pavei et al., 2017). Thus, measuring and analyzing ground reaction forces at increasing speeds is essential for investigating mechanics during race walking, even more so than in normal walking and running. Every type of locomotion, whether animal or human, has its own "locomotor signature," ultimately represented by the trajectory of the body's center of mass (BCoM) (Minetti et al., 2011). The same authors conducted an analysis of ground reaction forces and BCoM trajectory during race walking across a wide range of speeds and compared the three components of GRFs in normal walking and running.

Comparing the GRFs between race walking, normal walking, and running, some differences were observed. Vertical forces were higher in running, while in race walking, they seemed to increase with speed following the same trend as walking values at higher speeds. The behavior of BCoM is different in race walking compared to walking, especially in the support phase, due to the difference in the arc length along which BCoM moves. (Usherwood et al., 2012). In race walking, BCoM during the support phase does not move along a circular arc with the length of the leg as the radius (Pavei et al., 2017) but descends similarly to running. This could explain why the maximum value of the vertical force does not drop below body weight. In the propulsive phase, it was observed that the ground reaction force values are comparable between race walking and running. At the same time, the inversion between braking and propulsion in race walking occurs earlier than in running, and the braking time is shorter, resulting in a higher value of the ground reaction force.

A comprehensive analysis of ground reaction forces shows that race walking shares characteristics with both normal walking and running. These aspects are demonstrated by the distinct kinematic and dynamic features of race walking, which are remarkable. These characteristics generate different patterns in race walkers, but they do not alter the 3D trajectory of the body's center of mass and the associated spatiotemporal parameters, and do not appear to be linked to the performance level of the athletes.

The authors Hanley and Bissas highlighted in their study (Hanley & Bissas, 2016) the analysis of how the lower limbs work during race walking in elite athletes. For this purpose, 17 athletes of both genders performed race walking at competitive pace, recording ground reaction forces (at a frequency of 1000 Hz) using high-speed video recordings (at 100 Hz). Moments, work and power, step length and frequency, as well as estimated speed, were analyzed accordingly.

It was found that the hip flexors and extensors were the main sources of energy (averaging 24.5 J (±6.9) and 40.3 J (±8.3), respectively), while the plantar flexors (averaging 16.3 J (±4.3)) contributed to the energy generated in the late stance phase. Additionally, it was observed that the knee performed significant work ($p<0.001$) during the swing phase (averaging -49.1 J (±8.7)), with the knee extensors absorbing more energy, which is associated with smaller changes in speed during support. Furthermore, the knee flexors performed a significant portion of the work (averaging -38.6 J (±5.8)), and frequent injuries to the hamstring muscles are likely a result of their role in decelerating and controlling knee flexion during the phases of race walking.

Therefore, special attention should be paid to the important contributions of the thigh and leg muscles to energy generation, and efforts should be made to encourage the development of knee flexor strength to reduce the risk of injuries (Hanley & Bissas, 2016).

Another approach to biomechanical analysis of the lower limb in racewalking is the analysis of joint moments, powers, and *muscle group activity* (determined through electromyography).

To investigate these aspects, Hanley and colleagues conducted a study involving twenty international racewalkers, both male and female. They underwent laboratory training to enable biomechanical evaluations. For this purpose, the authors collected ground reaction forces (at a frequency of 1000 Hz), which were synchronized with high-speed two-dimensional videography (at 100 Hz) and electromyography of seven lower limb muscles (at 1000 Hz). In addition to measuring key performance variables, they calculated speed and step length, as well as normalized joint moments and powers. In racewalking, the rule requires the knee to be in extension and well-controlled from initial contact to midstance, and the leg functions as a rigid lever that amplifies the ground reaction force effect on the lower limb.

From a muscular standpoint, the primary factors contributing to energy generation for propulsion are the hip extensors during swing and at initial contact, as well as the plantar flexors. Knee control ensures that the leg is crucial for advancement during the swing phase. Therefore, knee flexors undergo a significant energy absorption phase during the swing phase.

Under the aspect of muscular electrical activity, Hanley and colleagues (Hanley & Drake, 2016) evaluated the effectiveness of six exercises commonly used by racewalkers due to their ability to activate key muscles. Muscle activity of eight lower limb muscles was monitored using electromyography on 10 young racewalkers while they performed the six exercises on a treadmill.

To measure the contact time and flight time, two force plates were used and the results were compared with the muscle activity recorded during normal walking at competition pace. Overall, the analyzed exercises resulted in higher activation of key muscles such as the gluteus maximus, rectus femoris, and vastus lateralis. However, they did not have the same benefit regarding the activity of the biceps femoris and tibialis anterior, two muscles that are often at risk of injury in racewalking.

Amplitudes of EMG activity in the gastrocnemius and soleus muscles increased significantly during this period, indicating an eccentric loading of the calf muscle-tendon unit. In the late stance phase, the activity of the calf muscles gradually decreased, while preparation for toe-off was controlled by a strong plantar flexor moment generated by energy, reaching its peak at approximately 80% of the total step time. Subsequently, this moment rapidly decreased, and a small dorsiflexor moment appeared, with a reversal of the EMG pattern from calf muscle activity to tibialis anterior activity.

The EMG recordings showed slight activity of the rectus femoris during the early swing phase and increased activity of the biceps femoris during the late swing phase, while the activity of the vastus lateralis gradually increased at heel strike. In the late swing phase, hip extension occurred due to the extensor moment generating energy, with high EMG activity recorded in the two hip extensors analysed, the gluteus maximus, and especially the biceps femoris.

The moment of the plantar flexors, generating energy with a relatively short duration, seems to be an attempt to "unlock" the ankle from a dorsiflexed position to allow for smooth landing and to engage the ankle earlier in the support phase. This active landing could be a characteristic of elite performers, considering its absence in studies of less skilled walkers, where a more passive landing occurs (Hoga et al., 2006; White & Winter, 1985). In the late support phase, the moment of the ankle plantar flexors generated the greatest mechanical energy source during the propulsive phase (4.5 ± 0.9 W · kg−1). The moment of the plantar flexors, absorbing energy, represents an important source of elastic energy storage in the gastrocnemius and soleus muscles, whose release contributes to the final plantar flexion movement (Zajac et al., 2003), as suggested by the EMG graphs showing diminished activity in the anterior calf muscles before toe-off.

At the hip, the gluteus maximus contracts first during mid-swing to stop flexion and then contracts together with the biceps femoris to generate energy and reverse the hip movement into extension. The magnitude of this extensor moment has been correlated with the speed and cadence of the marching step, confirming the crucial role of hip extensors just before the contact phase. In the early support phase, a large extensor moment continues hip extension.

Nowadays, technology is an essential component in sports, playing a significant role in improving training and evaluation processes.

Thus, the use of a wearable inertial system is proposed for developing new biomechanical indices aimed at evaluating performance and identifying irregularities in marching. These indices are built based on five inertial parameters: ground contact loss time, step duration relative to ground contact loss, step length ratio, step cadence, and continuity degree. Caporaso thus initiated a discussion on biomechanical indices personalized for elite marchers and graphically represented for intuitive analysis of performance and irregularities. From this graph, a synthetic index reflecting the overall athlete's gesture was obtained. The validation of these biomechanical indices was conducted in field tests involving nine elite marchers wearing an inertial sensor placed at the level of the lumbar spine (L5-S1). Statistical analysis was used to assess the quality and reliability of the proposed indices and their representations.

The results obtained indicated that these biomechanical indices can be successfully integrated into a wearable inertial system, providing assistance in training processes and competition evaluation. (Caporaso et al., 2020)

Conclusions

The racewalking event is a highly complex technical discipline, with rules that distinctly affect the kinetics of lower limb joints and electromyography (EMG) readings. By conducting a unique study that combines muscle moments and powers with EMG in elite athletes, we have provided evidence for the role of certain lower limb muscles and associated joint movements. The rules governing knee behavior impose a rigid lever role for much of the support phase, and the rules of the event influence the development of a balancing pattern crucial in generating forward momentum. Joint moments are significant elements in balance, influencing walking speed. Additionally, hip extensor moments during the initial support phase, along with plantar flexor moments during the final support phase, were key factors in generating the energy required for propulsion.

The conclusions drawn from the reviewed literature suggest the necessity of developing training regimes that enhance the strength of key muscle groups, particularly those around the hip, to facilitate propulsion and reduce the risk of injury during the balancing phase.

In conclusion, the biomechanics of the lower limb play a crucial role in the performance and health of racewalkers, and understanding these principles can contribute to optimizing training and performance in this specific athletic event.

References

Cairns, M. A., Burdett, R. G., Pisciotta, J. C., & Simon, S. R. (1986). A biomechanical analysis of racewalking gait. *Medicine and science in sports and exercise*, *18*(4), 446-453. https://doi.org/10.1249/00005768-198608000-00015

Caporaso, T., Grazioso, S., Di Gironim, G., & Lanzotti, A. (2020). Biomechanical indices represented on radar chart for assessment of performance and infringements in elite race-walkers, *Sports Engineering*, *23*(1). DOI: https://doi.org/10.1007/s12283-019-0317-2

Cavagna, G. A., & Franzetti, P. (1981). Mechanics of competition walking. *The Journal of Physiology*, *315*(1), 243–251. https://doi.org/10.1113/jphysiol.1981.sp013745

Cavagna, G.A. (1975). Force platforms as ergometers. *J. Appl. Physiol. 39*(1), 174–179. DOI: https://doi.org/10.1152/jappl.1975.39.1.174

Hanley B., Tucker C. B., & Bissas A. (2018). Differences between motion capture and video analysis systems in calculating knee angles in elite-standard race walking, *Journals of Sports Sciences*, *36*(11), 1250-1255. DOI: https://doi.org/10.1080/02640414.2017.1372928

Hanley, B., & Bissas, A. (2013). Analysis of lower limb internal kinetics and electromyography in elite race walking, *Journals of Sports Sciences*, *31*(11), 1222-32. doi: https://doi.org/10.1080/02640414.2013.777763

Hanley, B., & Bissas, A. (2016). Analysis of lower limb work-energy patterns in world-class race walkers", *Journals of Sports Sciences*, *35*(10), 960-966. DOI: https://doi.org/10.1080/02640414.2016.1206662

Hanley, B., & Drake, A. (2016). Effectiveness of Popular Race Walking Drills in Activating Key Muscles, *New Studies in Athletics*, *31*(3/4), 81-88. https://eprints.leedsbeckett.ac.uk/id/eprint/4622/

Hanley, B., (2014). Biomechanical Analysis of Elite Race Walking. Doctoral thesis, Leeds Metropolitan University. https://eprints.leedsbeckett.ac.uk/id/eprint/591/

Hoga, K., Ae. M. Enomoto, Y. Yokozawa, T., & Fujii, N. (2006). Joint torque and mechanical energy flow in the support legs of skilled race walkers. *Sports Biomechanics*, *5*(2), 167–182. doi: https://doi.org/10.1080/14763140608522872.

Homenkov, L.S., (1977). *Atletism* [Athletics]. Sport-Turism.

Hongzhao, W., Ming, H., Xiangde, A., Yong, L., Ko, O., Desheng, L., Qiuchen, H., De, C., Lu, Y., & Hitoshi, M. (2016). Kinematics of the forefoot in the horizontal plane during progressive pace barefoot racewalking on a treadmill after aerobic exercise load, *Journal of Physical Therapy Science*, *28*(2), 515–518. doi: https://doi.org/10.1589/jpts.28.515

IAAF (2015). Competition rules 2014 – 2015 [Internet], Available from https://cdn1.sportngin.com/attachments/document/0086/7190/IAAF_Competition_Rules_2014-2015.pdf

Levine, D., Richards, J., & Whittle, M. W. (2012). *Whittle's Gait Analysis* (5th ed.). Churchill Livingstone, London.

Minetti, A.E., Cisotti, C., & Mian, O.S. (2011). The mathematical description of the body centre of mass 3D path in human and animal locomotion. *Journal of Biomechanics, 44*(8), 1471–1477. doi: https://doi.org/10.1016/j.jbiomech.2011.03.014.

Pavei, G., & La Torre, A. (2015). The effects of speed and performance level on race-walking kinematics. *Sport Sciences for Health*,*12*(1), 1-13. DOI: https://doi.org/10.1007/s11332-015-0251-z

Pavei, G., Seminati, E., Cazzola, D., & Minetti, A.E. (2017). On the Estimation Accuracy of the 3D Body Center of Mass Trajectory during Human Locomotion: Inverse vs. Forward Dynamics. *Frontiers in Physiology, 8*(8), 129. doi: https://doi.org/10.3389/fphys.2017.00129.

Skublewska-Paszkowska, M., Lukasik, E., Smolka, J., & Nawroka, M. (2018). New Automatic Algorithms for Computing Characteristic of Three Dimensional Pelvic and Lower Limb Motions in Race Walking, Conference: 11th International Conference on Human System Interaction (HSI), DOI: https://doi.org/10.1109/HSI.2018.8431079

Usherwood, J. R., Channon, A. J., Myatt, J. P., Rankin, J. W., & Hubel, T. Y. (2012). The human foot and heel-sole-toe walking strategy: A mechanism enabling an inverted pendular gait with low isometric force? *J. R. Soc. Interface 2012, 9*(75), 2396–2402. DOI: https://doi.org/10.1098/rsif.2012.0179

Villarroya, M. A., Casajús, J. A., & Pérez, J. M. (2009). Temporal values and plantar pressures during normal walking and racewalking in a group of racewalkers. *Journal of Sport Rehabilitation, 18*(2), 283-295. DOI: https://doi.org/10.1123/jsr.18.2.283

White, S. C., & Winter, D. (1985). Mechanical power analysis of the lower limb musculature in race walking. *International Journal of Sport Biomechanics, 1*(1), 15–24. DOI: https://doi.org/10.1123/ijsb.1.1.15

Zajac, F. E., Neptune, R. R., & Kautz, S. A. (2003). Biomechanics and muscle coordination of human walking: Part II: Lessons from dynamical situations and clinical implications. *Gait and Posture, 17*(1), 1–17. doi: https://doi.org/10.1016/s0966-6362(02)00069-3