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BIOMECHANICAL ANALYSIS OF ANKLE DURING THE STANCE PHASE OF GAIT ON VARIOUS SURFACES: A LITERATURE REVIEW

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ABSTRACT
The purpose of this article is to review the literature that deals with the biomechanical analysis of the ankle during gait stance phase on slopes, on uneven and rock surfaces, on sand, and on grass surfaces, as well as to present the observed differences. Methods. The literature was searched in the databases of PubMed and Google Scholar, for the years of 2005–2015. The keywords were: biomechanics, gait analysis, ankle joint, stance phase, uphill walking, downhill walking, sand surface, uneven surface, grass surface, and ballast. Results. The kinetic and kinematic gait behaviour is directly influenced by the surface on which it is being performed. The uphill or downhill surfaces, the surfaces of stone, sand, grass, and uneven surfaces have a direct impact on the biomechanics on joints of the lower limb, changing the energy cost, muscle activation, the resulting mechanical work, ground reaction forces and balance, and the parameters of the gait cycle. All these changes are raising many questions about the safety and comfort of these surfaces. In the structures of the foot, ankle and lower leg high compressive and rotational forces are transmitted resulting in injuries in these regions. Conclusions. Each surface has its own advantages and disadvantages, changing the biomechanics of the lower extremity and particularly the ankle. According to the purpose that one wants to achieve they can choose a suitable surface. To prevent injuries and falls, we must choose shoes that fit well, are comfortable with cushioning, and have a feeling neither too hard nor too soft, with laces and low collar.

Key words: biomechanics, ankle joint, stance phase, uphill walking, downhill walking, sand surface, uneven surface, grass surface

Introduction

In daily life, human gait takes place on variable terrain, with different surface characteristics. These could be ordinary surfaces such as grass or sand, slippery surfaces such as ice, uneven ground (rock environments), and inclined ground (ascent, descent). Most falls occurring in real world conditions are caused by environmental obstacles like uneven surfaces. Walking on these surfaces brings biomechanical and kinaesthetic disturbances. If someone cannot adapt their gait appropriately to the surface, it could then lead to a fall, resulting in an injury. Therefore it is essential to study the gait adaptation to uneven surfaces in order to reduce the risk of falling.

The ankle joint plays an important role in gait adaptation on different surfaces because it receives the whole weight of the body and even more during each step. Ankle is also the joint most adaptable to changes of the surface. The appropriate way to study the biomechanical behaviour of the ankle joint is during the stance phase of gait, which starts when the foot touches the ground and ends when the anterior foot detaches it.

The purpose of the present review is to deeply understand the kinetic and kinematic changes which occur in the lower limb and especially in the ankle during walking on different surfaces. This may contribute to fall prevention and to a better selection of the walking surface according to the goal that one wants to achieve.

Analysis of the walking cycle

Walking is generally defined as a means of human locomotion in the space. According to Washburn (1960) [1], the human gait is the way that the human body has found to cover long distances with the least possible loss of energy. The ability to activate the suitable muscles of the limbs as an answer to the surface's changes is essential for human locomotion [2]. The main muscles of the lower extremity are more activated during the stance phase of gait [3], when they have to produce work into the centre of mass and to support the human weight.

The gait cycle is the time interval between two successive heel contacts of the same limb to the ground. It consists of the stance and the swing phases.

Stance phase duration is the time when the limb remains in contact with the ground during a single gait cycle [4, 5]. *Stride length* is the horizontal distance between two successive placements of the same limb during the gait cycle [6]. *Step length* is the horizontal distance between a placement of the one limb and the same placement of the opposite limb during the gait cycle. It is usually measured as the distance between the heel strike of the one foot to the heel strike of the opposite foot gait [7]. *Gait rhythm* is the number of steps performed

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by a person per a unit of time. It can be measured in steps per second or per minute, which is more common. A reduced step length will cause an increased gait rhythm at any speed [4]. *Speed* is the rhythm of the object's forward horizontal movement. It is measured as a distance covered per a unit of time (m/s).

Women have a tendency to walk with smaller and faster steps as compared with men at the same speed [4].

Material and methods

An electronic search of PubMed, Google Scholar, Europe PubMed Central, and Science Direct databases was performed in order to examine the recent literature concerning the biomechanical responses of the ankle to different surfaces during the stance phase of the gait. The terms biomechanics, gait analysis, ankle joint, stance phase, uphill walking, downhill walking, sand surface, uneven surface, grass surface, and ballast were used in different compositions. We accepted only papers written in English, which were published within the recent decade, especially during the recent five years, with the study populations consisting of humans. The studies were reviewed on the basis of their title and abstract. The total of 31 papers were reviewed; 24 of them were published during the recent quinquennium. Finally, 17 full-text articles met our eligibility criteria, of which 14 were published in the recent five years. We also used scientific books, in English or in Greek, referring to human anatomy, biomechanical analysis of the lower limb, and gait analysis. The total of 37 citations were included.

Results and discussion

Biomechanical analysis of the ankle when walking on various surfaces

Gait on inclined surfaces (ascent-descent)

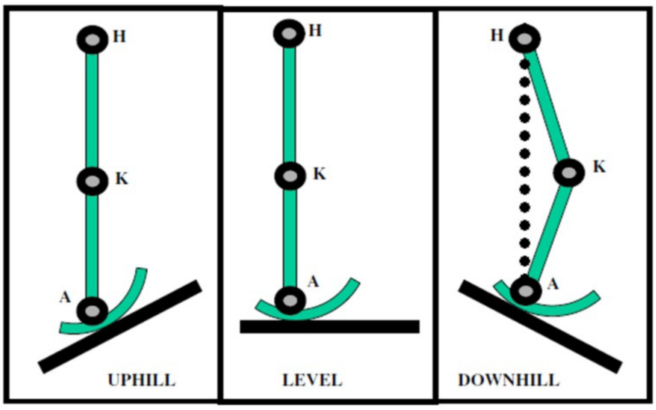
During uphill walking people seem to have a slower rhythm and a longer stride length, staying longer at the stance phase. Descent surface is associated with a reduced stride length and a faster rhythm, causing a reduced stance phase duration [8].

Ankle is the most adaptable joint during uphill walking and knee is the most adaptable joint during downhill walking (Figure 1) [8].

Compared with level walking, downhill walking is associated with higher gait variability, which increases the risk of falling [9, 10].

Muscle activity during gait in ascent and descent

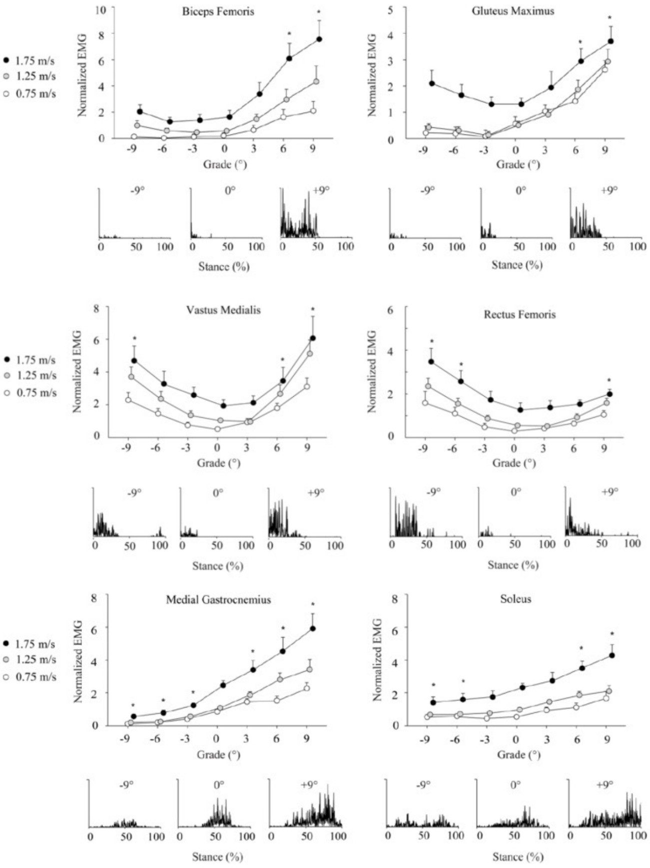
Ankle extensor muscle activations during the stance phase gradually increase to steep ascent at various speeds (Figure 2). Compared with level walking, these increases are statistically significant at all ascent grades for *gastrocnemius* (G), at grades steeper than 3° for *gluteus maximus* (GM), *biceps femoris* (BF), *vastus medialis* (VM) and *soleus* (SOL), and at grades steeper than 6° for *rectus femoris* (RF).



Source: Hansen et al. 2004 [7]

Figure 1. Behaviour of the knee-ankle-hip system of gait in level ground, uphill and downhill surface. H – hip, K – knee, A – ankle

During the stance phase, only the knee extensor muscle activations (RF, VM) increase to steep descent at all speeds (Figure 2). Compared with level surface,



Source: Franz and Kram 2012 [11]

Figure 2. Activity of extensor muscles of the hip, knee, and ankle during downhill and uphill gait at various speeds during the stance phase

these activations are statistically significantly higher at descent grades steeper than 3° for RF and at grades steeper than 6° for VM.

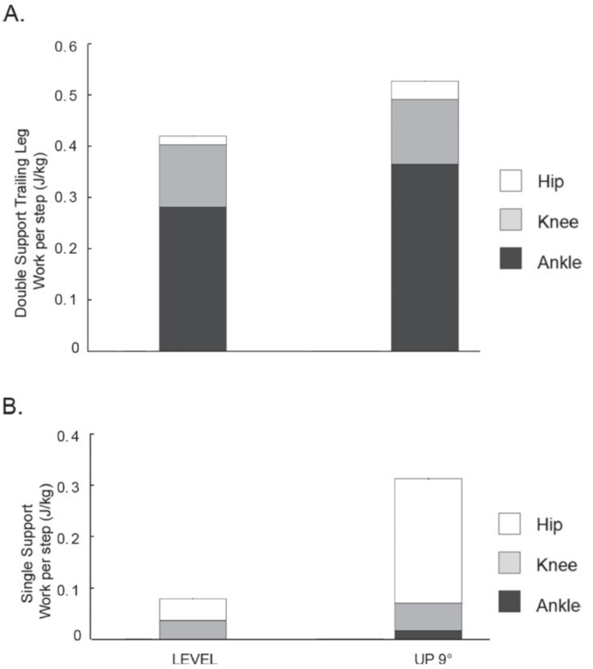
Hip extensor muscle activations (GM: 345%, BF: 35%) increase statistically significantly more than the ankle extensor muscle activations (SOL: 136%, G: 175%) to walk up 9°, compared with level walking. These findings prove that hip and ankle extensor muscles play an important role in uphill walking.

On average, knee extensor muscle activities (RF: 310%, VM: 246%) increase to downhill walking at grades steeper than 9°, compared with level walking. These results show that downhill walking could be difficult for people with quadriceps muscle atrophy and inability to extend their knee.

In conclusion, hip, knee, and ankle extensor muscle activations increase during uphill walking. Only knee extensor muscle activations increase during downhill walking [11].

Production of mechanical work and ground reaction forces during walking in ascent and descent

During the double support phase of level walking, both limbs perform positive and negative external work simultaneously [12]. Both carry out gradually higher positive external work with steeper ascent grade and higher negative external work with steeper descent grade [13]. So, in contrast to level walking, the leading or the trailing leg performs up to 1/3 of the external work, which is produced during double support phase of uphill (positive work) or downhill (negative work) walking.



Source: Franz and Kram 2012 [11]

Figure 3. Average joint mechanical work per step performed during (A) double (trailing leg) and (B) single support

This finding shows that during uphill walking the hip and knee extensor muscles of the leading limb support the ankle extensor muscles of the trailing leg, in order to raise the centre of the mass and to overcome gravity by producing the maximum possible positive work (Figure 3). During downhill walking, knee extensor muscles of both limbs perform the maximum negative work, in order to reduce the centre of mass and to achieve resistance to gravity [13].

Running on inclined surfaces (ascent-descent)

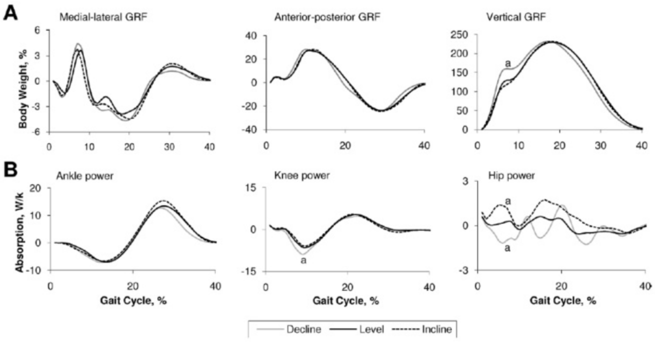
Uphill and downhill training is usually used by ultra runners because of its effectiveness in circulatory system and in endurance [14]. However, this type of training could cause kinetic changes (in ground reaction forces and joint power) which may contribute to running injuries.

Running on uneven terrain has been associated with increased oxygen consumption, heart rate, blood lactate concentration and lower limb muscle activity.

During uphill running, the rhythm is higher and the stride length is reduced as compared with level walking. On the contrary, there are not many differences between downhill running and level running.

No important changes have been found at the ankle, knee, or hip during running at a constant velocity on any level. However, changes have been observed in knee and hip power. At the beginning of the stance phase, hip power generation is increased during incline running, but hip power absorption is increased during decline running. Knee power absorption is increased during decline running. No statistically significant changes have been found in ankle power during running on any level. Only an increase has been noted in the impact peak of the vertical ground reaction force during decline running, but no changes have been found in the non-vertical components (Figure 4) [15].

The absence of important changes in lower limb joints during incline running may indicate alterations in rhythm and stride length as a result of the runner's effort to hold a constant velocity with changes in ground slope [16].



Source: Telhan et al. 2010 [15]

Figure 4. (A) Three-dimensional (A) ground reaction force (GRF) and (B) joint powers during stance for decline (gray), level (black), and incline (dotted) running

Gait on uneven ground

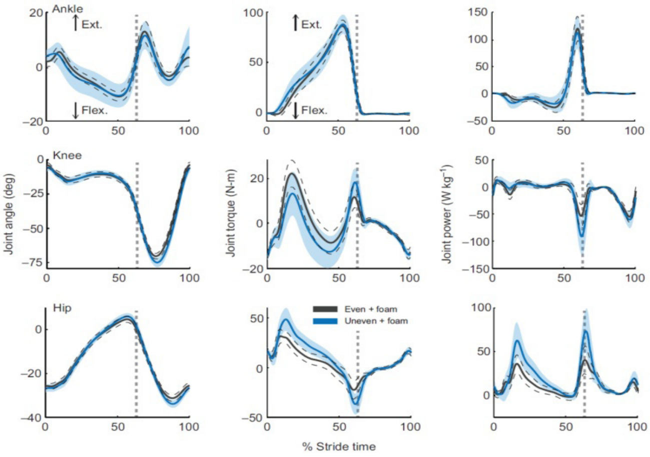
There are many factors which may contribute to larger energy consumption during walking on uneven ground comparing with walking on level ground. Altering stride parameters during gait is one of these. Elderly adults usually walk with shorter and wider steps [17]. But young adults alter their gait patterns when they have a permanent kinetic or visual situation [18, 19]. If these are strategies to preserve gait stability, young adults may use these gait patterns on uneven ground.

Changes in kinetic and kinematic gait when walking on uneven ground

According to Donelan et al. [12], walking on uneven ground is associated with slightly shorter and altered stride. The average stride decreases only by 4% and the increase in stride width is not statistically significant [20].

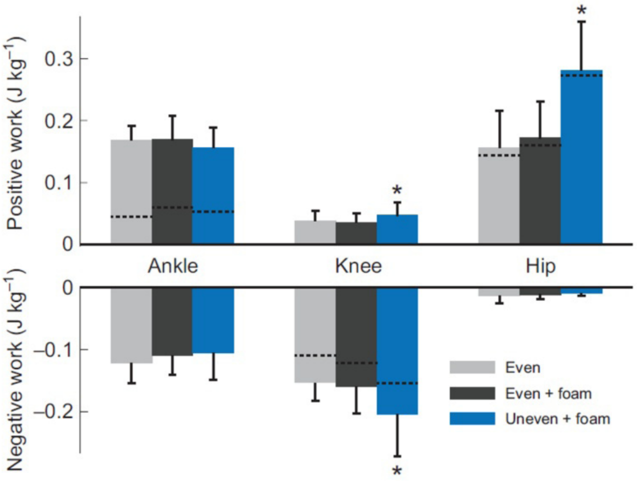
The kinematic factors do not appear statistically significant changes during walking on uneven surface. But the hip and knee mechanical work increase as compared with walking on smooth ground. Walking on uneven terrain causes a variety of changes in kinetics and kinematics (Figure 5).

Previous researchers examined qualitatively the sagittal plane joint angles on uneven surface. They found slightly greater hip and knee flexion during the mid-swing phase, which may be associated with a higher ground distance of the swing foot. The mean ankle trajectory slightly changed (Figure 5). However, they observed greater alterations of the joint moments during the stance phase. Increased knee flexion and hip extension have been found at mid-stance phase. But at the end of the stance phase (push-off), greater knee extension and hip flexion have been observed.



Source: Voloshina et al. 2013 [21]

Figure 5. Mean trajectories for ankle, knee, and hip are plotted against percent stride time for uneven and even terrain (both with foam) conditions. Shaded area denotes standard deviation across subjects for uneven + foam; dashed lines for even + foam. Strides start and end at same-side heel-strike; dashed vertical gray lines indicate toe-off



Source: Voloshina et al. 2013 [21]

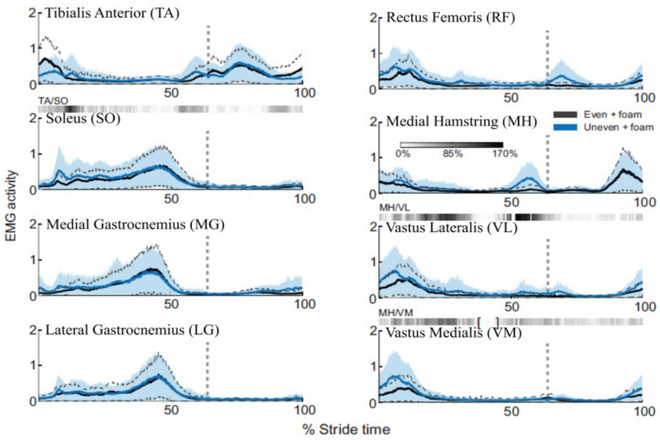
Figure 6. Joint work per stride for three terrain conditions. Values shown are positive and negative work for ankle, knee, and hip, with error bars denoting standard deviations. Dashed lines indicate net work for the particular joint and condition. Asterisks signify a statistically significant difference of the uneven + foam condition from the other two conditions

During walking on uneven terrain, the main changes in joint power concern the knee and the hip. Voloshina et al. [21] found that knee power increased approximately by 65% and hip power by 85%, especially during the push-off. Hip power also appears an increase by 75% at mid-stance, which occurs at 20% of stride time. Joint trajectories are also more variable (Figure 5). Hip and knee angle variability increased approximately by 30% and ankle angle variability increased more than double. Moreover, hip, knee, and ankle power variability increased by 50% or more.

Walking on uneven surface causes biomechanical alterations, which lead to increased joint work during a stride (Figure 6). About the knee, positive and negative work was found to be increased approximately by 28% and 26%, respectively. Positive hip work increased by 62%, but negative work appeared to undergo no statistically significant changes. Ankle work did not change statistically significantly (Figure 6) [21].

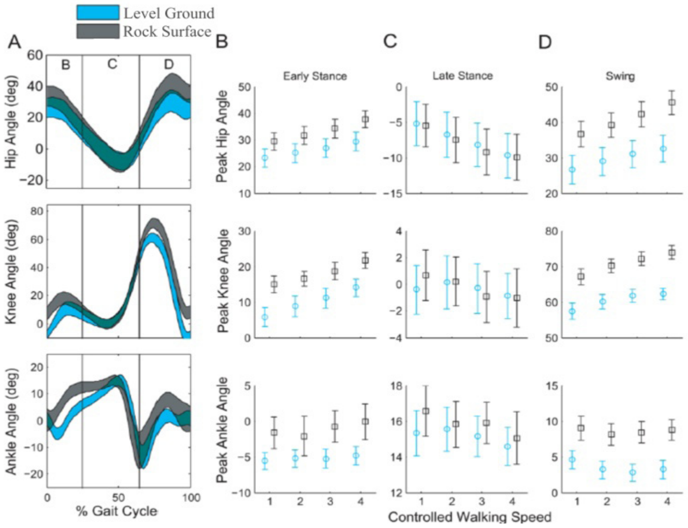
Muscle activity during gait on uneven ground

Walking on uneven terrain is associated with greater muscle activity, muscle activity alterations and mutual muscle contraction (Figure 7). On average, hip muscle activations increase. VM increases by 49%, *vastus lateralis* (VL) by 60%, RF by 54%, and medial hamstring by 47%. As for the lower leg, the SOL muscle activity increases by 28% and G muscle activity by 17%. *Tibialis ante-*



Source: Voloshina et al. 2013 [21]

Figure 7. Averaged electromyographic (EMG) activity versus stride time for even and uneven terrain conditions. Strides start and end at same-side heel-strikes; dashed vertical gray lines indicate toe-off. Envelopes represent standard deviations for uneven (shaded area) and even terrain (dashed lines) conditions (both with foam). Gray bars denote statistically significant increases in mutual muscle contraction, with darker colours indicating larger percent increases, from even terrain mutual muscle contraction to uneven terrain mutual muscle contraction. Brackets show the time of decreased muscle contraction



Source: Gates et al. 2013 [22]

Figure 8. (A) Bands represent the mean ± standard deviation of the average joint angle. (B–D) Average peak kinematic parameters are shown for each of the four controlled walking speeds on both surfaces

rior (TA) and *lateral gastrocnemius* (LG) did not show statistically significant changes in stride, although TA has decreased activity in the early 10% of stride.

Alterations were also found in mutual contraction during the entire stride of the three pairs of antagonistic muscles (Figure 7) [21].

Gait on rock surface

Temporal-spatial variability when walking on rock surfaces

During a walk on a rock surface, the step length width and time variability are increased, comparing with walking on level ground. Step time was found to decrease with increasing speed [22].

Previous researchers observed that stride alteration was associated with higher rates of falls [23, 24]. Therefore, walking on a rock surface increases the risk of falling. But stride alteration provides only one indirect measure of stability [25]. Moreover, the measures of stability do not show which specific kinematic alterations people use in order to keep their balance.

Changes in kinematics during walking on rock surfaces

During walking on rock terrain people contact the surface with a flatter foot than during walking on level ground, in order to prevent a possible slip. This is achieved by lowering the required coefficient of friction between the shoes and the floor [22, 26].

Since the foot is almost flat at heel strike, no plantar flexion was observed by previous researchers. But they mentioned an increase in knee flexion and a smaller increase in hip flexion (Figure 8A, B) [22].

At mid-stance of walking on rock terrain, a quick ankle dorsiflexion was observed. But prior to the toe-off phase, a similar ankle dorsiflexion still remained (Figure 8C) [22].

During the swing phase on rock surfaces, people walk with increased hip and knee flexion and ankle dorsiflexion. Unlike with the hip and the knee, ankle dorsiflexion does not show signs of any statistically significant change by increasing the speed. But by increasing the velocity on level ground, ankle dorsiflexion decreases (Figure 8D) [22].

Increased hip, knee, and ankle flexion during early stance and terming swing contribute to lowering the centre of mass in order to strengthen the balance. Overall, people adapt their gait appropriately to the destabilizing terrain so that they maintain their balance and avoid possible falls.

Muscle activity during gait on rock surfaces

During walking on a rock surface, lower limb muscle activations are higher, compared with level walking. The situation of the ballast importantly impacts the mean and maximum muscle activation for all muscles of the lower limb. The increased muscle activations help to control the forces which act on the lower limb joints. But they may increase the compressive force and the local muscle fatigue [27].

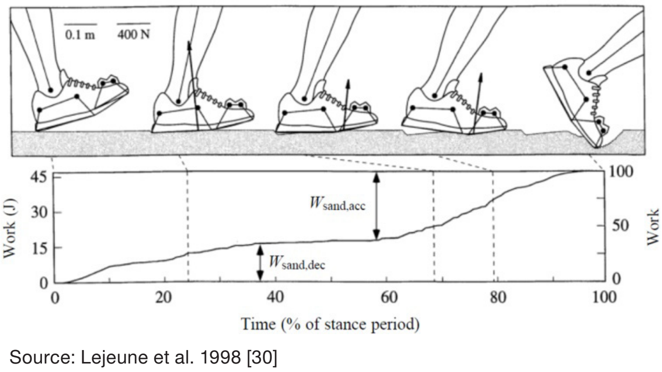
Gait on a sand surface

Changes in kinematics when performing walking or running on a sand surface

Previous researchers found that walking on sand terrain was associated with significantly decreased average speed, maximum speed, average acceleration, maximum acceleration, average stride length, and flight time. On the contrary, the average energy cost and the contact time were increased, as compared with level walking [28].

During locomotion on a hard and slippery surface, the external work is essentially zero because air resistance is negligible and the foot does not slip or dislodge. In contrast to movement on hard surface, locomotion on sand causes the foot to move the sand, which results in additional external work [28, 29]. According to Zamparo et al. [29], the foot has the tendency to slip backwards, which may lead to a decreased acceleration during the push phase of the gait (Figure 9). Moreover, sand may be a more suitable surface for performing exercises with a direction change because it allows to achieve maximum deceleration values. These findings could be very important for training programs focused on eccentric contraction during prevention or rehabilitation.

The instability of the sand terrain is the main cause of increased energy cost. Training on sand surface gives the advantage to perform maximal intensity exercises (with high energy cost), but without reaching maximum speed. This is a remarkable tool for injured athletes because they can train with safety at a high metabolic intensity [28].



Source: Lejeune et al. 1998 [30]

Figure 9. Movement of the foot into the sand in the sagittal plane (upper panel) and the cumulative work performed on the sand (lower panel) for the stance phase of a walking step. The foot is drawn when 0, 25, 50, 75 and 100% of the total work has been done on the sand, as indicated by the dashed lines. $W_{sand,dec}$ represents the work performed on the sand during the deceleration of the centre of mass (COM), and $W_{sand,acc}$ represents the work performed on the sand during the acceleration of the COM. The sand surface records the deepest penetration of the foot into the sand. The arrows in the upper panel indicate the point of application, direction, and magnitude of the ground reaction force vector

Figure 9 represents the mechanical work done on the sand for the stance phase of a walking step with time. Almost all of the muscle-tendon work performed during walking on the sand is obtained in the second part of the stance phase, when the centre of mass is accelerated forward. During the middle of the stance phase, despite the high forces, no important work is carried out on the sand because there is no significant displacement of the foot. The former also happens during running on the sand.

When the vertical forces are high (e.g. between the period from 20 to 80% of the stance phase), the foot just touches the surface. The maximum penetration of the foot into the sand (average 74% at walking, 78% at running) was noted at the end of the stance phase because then the forces were reduced and directed almost horizontally.

The situation of running on sand is different. In total, the work performed by a person on sand is the same as that on a hard surface. Running on the sand differs a lot from running on a stable surface.

Sand is like a shock absorber; it only absorbs energy and produces work on the environment, which represents the energy lost from the subject. But a stable surface returns the higher amount of energy, which is absorbed, by increasing the production of the positive work. As a result, there is a performance improvement [30, 31].

Muscle activity during walking and running on sand surfaces

According to Pinnington et al. [32], walking or running on sand requires higher knee and ankle muscle co-contraction. Moreover, joints, muscles, and tendons accept lower stress during exercising on sand. Training on sand is applied as an alternative way to normal sessions during the competive period for recovery.

Carrying out exercises on sand might be beneficial during the rehabilitation of an injury when running on grass is painful (e.g. after anterior cruciate ligament operation). Of course, performing exercises on sand requires a sufficient level of strength. Obviously sand surface is an important tool which helps athletes to reach their final goal with safety [28].

Gait on grass

Natural grass surface is stiffer than sand, but both have exactly the same mechanical features. Of course, natural grass is characterized by lower prices, which approach the prices of a hard and inelastic surface. Moreover, grass and sand terrains are bound with similar risk, such as the surface instability, potholes, and surface disparity [33, 34]. Table 1 represents changes, among others, between sand and grass surfaces, Table 2 – between sand and natural and artificial grass surfaces.

Table 1. Average speed and steps when walking on concrete, grass, dry sand and wet sand

	Concrete	Grass	Dry sand	Wet sand
Walking speed (km · h^{-1})				
Male	5.6 ± 0.6	5.6 ± 0.6	4.9 ± 0.4	5.4 ± 0.4
Female	5.6 ± 0.4	5.7 ± 0.5	5.0 ± 0.5	5.4 ± 0.5
All	5.6 ± 0.5	5.6 ± 0.5	5.0 ± 0.5	5.4 ± 0.4
Steps taken				
Male	188 ± 14	183 ± 13	204 ± 12	192 ± 11
Female	192 ± 11	188 ± 10	211 ± 13	197 ± 11
All	190 ± 13	186 ± 12	207 ± 12	194 ± 11

Source: Leicht and Crowther 2007 [35]

Table 2. Mean various parameters during walking on natural and artificial grass compared with walking on sand

	Natural grass	Artificial turf	Sand
Duration (s)	1.98 ± 0.06	1.99 ± 0.09	2.28 ± 0.09**
Average speed (m · s^{-1})	6.05 ± 0.2	6.01 ± 0.29	5.27 ± 0.23**
Maximum speed (m · s^{-1})	7.04 ± 0.47	7.12 ± 0.35	6.22 ± 0.41**
Average acceleration (m · s^{-2})	2.97 ± 0.29	2.98 ± 0.20	2.62 ± 0.15**
Maximum acceleration (m · s^{-2})	7.05 ± 1.95	7.00 ± 1.70	5.94 ± 1.18**
Maximum deceleration (m · s^{-2})	8.00 ± 1.26	7.97 ± 2.09	9.13 ± 1.57*
Average energy cost (J · kg^{-1} · m^{-1})	17.13 ± 1.68	17.17 ± 1.14	21.97 ± 1.19**
Average metabolic power (W · kg^{-1})	103.92 ± 12.17	103.91 ± 9.59	116.26 ± 9.14**
Average mechanical power (W · kg^{-1})	17.99 ± 2.10	18.01 ± 1.66	13.86 ± 1.13**
Number of contacts	8.92 ± 0.35	8.90 ± 0.30	10.05 ± 0.46**
Average stride length (m)	1.34 ± 0.06	1.34 ± 0.05	1.19 ± 0.05**
Stride frequency (Hz)	4.46 ± 0.31	4.46 ± 0.24	4.41 ± 0.26
Average flight time (s)	0.068 ± 0.008	0.068 ± 0.009	0.049 ± 0.006**
Average contact time (s)	0.151 ± 0.010	0.153 ± 0.013	0.180 ± 0.012**
Maximal ground reaction force (kN)	1.62 ± 0.17	1.61 ± 0.17	1.42 ± 0.15**

* $p < 0.05$, significant difference from natural grass values
** $p < 0.001$, significant difference from natural grass values
Source: Gaudino et al. 2013 [28]

Conclusions

We cannot point at one surface most suitable for walking or running with confidence. Each surface has its own advantages and disadvantages, causing different changes in lower limb biomechanics, especially in the ankle. We should choose particular surfaces according to the desired goal. For example, if we need higher safety with higher energy cost, the ideal surface could be sand. On the contrary, if we want very high energy cost with normal safety, inclined terrain would be an ideal option.

Since walking on different surfaces changes lower limb biomechanics, the choice of the shoe is very important. Previous researches proved that the usage of orthotics reduced the mobility of the posterior foot. Applying orthotics and shoes with soft soles (cushioning system) relieves pain in the heel and Achilles tendon [36]. Shoes with increased cushioning distribute the forces over a greater area of the plantar surface. Heavier shoes increase oxygen consumption and energy cost [37, 38]. Also, wearing shoes with increased heel height for a long period could lead to permanent Achilles tendon contraction and to a reduced plantar flexion. High collar shoes do not provide stability.

The wide variety of anatomical, physiological, and kinematic characteristics make the right choice of shoes difficult. But generally one should prefer comfortable, cushioned, and laced shoes, with a low collar and a normal sense of hardness [39].

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