Energy and Performance Aspects in Sport Surfaces

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Introduction

Each step, stride, jump, landing, etc. of an athlete requires the athlete to expend a certain amount of energy. If some of this energy can be reused, through energy return from the surface, the athlete can perform the same movement more efficiently. If the athlete expends the same amount of effort and performs the same amount of work, his performance will be increased if energy is returned from the surface. An obvious example of this is the energy stored in a trampoline. As an athlete lands, the kinetic energy of the athlete is stored in the deformation of the trampoline. The energy the trampoline returns to the athlete allows the athlete to return to his or her original height with much less effort than if the athlete was jumping off a rigid surface. Alternatively, if the athlete exerted the same effort as they would on a rigid surface, the maximal height obtained would be increased due to the additional energy provided by the trampoline.

Although to a smaller scale than the trampoline example, all sport surfaces are capable of returning energy to athletes. As the athlete contacts the sport surface, energy is transferred from the athlete, through the foot and shoe, into the surface. As the athlete leaves the surface, some of this energy can flow back in the opposite direction from the surface to the athlete. Thus, energy transfer to and from the surface can have a large influence on athletic performance. The magnitude of the energy returned from a sport surface to an athlete is a function of the amount of energy input into the surface minus the energy lost (Eqn. 1).

$$E_{return} = E_{input} - E_{lost} \qquad (1)$$

This equation is influenced by some physical constraints as well as different material and structural characteristics of sport surfaces.

The purpose of this paper is to discuss the factors that influence energy return in sport surfaces and to demonstrate that energy aspects of sport surfaces can influence sport performance.

Energy balance

Energy input

During each ground contact, an athlete performs work on the sport surface. The work performed results in deformation energy being input into the surface and is a function of the contact force (Eqn. 2). Large forces are exerted by athletes during sporting movements. Even simple movements like jogging can produce forces of over two times body weight and peak magnitudes can reach over ten times body weight for more intense activities like running jumps (Nigg, 1999). The larger the force, the greater the potential for energy storage in the surface.

$$W_{athlete} = \int \vec{F} \bullet d\vec{r} = \Delta E_{surface}$$

Forces that athletes exert on surfaces are necessary for energy storage in the surfaces, however, the actual magnitude of the stored energy depends on the properties of the surface. Energy storage is a function of surface stiffness and surface deformation (Eqn. 3).

$$E_{surface} = \frac{1}{2} k x^2 \qquad (3)$$

As can be seen from equation 3, energy return increases linearly with increasing material stiffness, k, and quadratically with increasing deformation, x. Deformation and stiffness are directly related, although inversely. For example, if stiffness is doubled, deformation is halved. The net result would also be a 50% reduction in the energy storage. Thus, the more compliant the surface, the larger the deformation and the greater the energy stored. Some studies have suggested that surface stiffness can have a large effect on the energy associated with human movement (Passmore and Durnin, 1955; Strydom et al., 1966).

Surface stiffnesses vary depending on their applications. In general, tumbling and gymnastics surfaces for floor exercises are more compliant than hardwood gymnasium floors (Table 1). These compliant surfaces allow very large deformations and result in high energy storage values.

Table 1. Approximate stiffness values, estimated deformation and associated potential energy storage of different sport surfaces (adapted from Stefanyshyn and Nigg, 2000a).

Surface	**Approximate Stiffness** [N/m]	**Defomation** [m]	**Energy** [J]
Tumbling floor	50,000	0.100	250
Gymnastic floor	120,000	0.050	150
Running track	240,000	0.010	12
Gymnasium floor	400,000	0.005	5

Energy lost

The amount of energy input into a surface is not going to be the amount of energy returned by the surface to an athlete (Eqn. 1). Some of the energy will be converted to aspects such as heat, sound and vibrations which do not benefit the performance of the athlete.

As a surface is loaded, it undergoes deformation and energy is input into the surface (Fig 1). However, as it is unloaded, some deformation, and therefore some energy, remains in the surface due to the time-dependent properties of the materials. Thus, in returning to its original shape, the work done by the surface on the athlete is less than the work done by the athlete to deform the surface. This energy that is dissipated in the surface is a material property that is common to all surfaces and can not be avoided. However, the magnitude of the energy dissipation can be influenced.

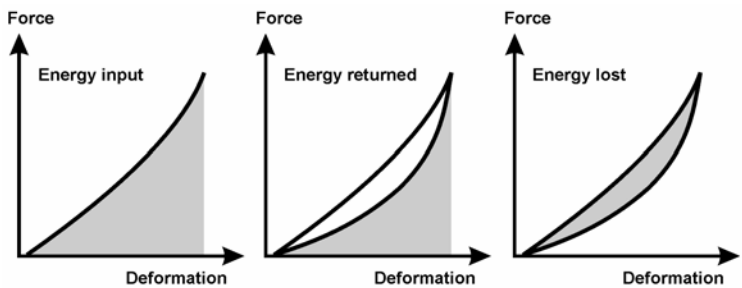

Fig. 1. Energy input, returned and lost in a sport surface. In each case the shaded region depicts the magnitude of the energy.

Energy loss can vary widely between different types of surfaces and even within surfaces constructed for similar purposes (Table 2). Drop tests were performed on a variety of surfaces using two different spherical masses (4 and 7.3 kg) and three different drop heights (5, 10 and 20 cm). The majority of the energy input into the infilled surface was lost (about 85%). The sand/rubber mixture in the infilled turf surfaces absorb a lot of energy and are not well suited to store and return energy.

Table 2. Results of energy loss values as measured from vertical drop tests using two spherical masses from three different drop heights.

Sample		**Energy Lost [%]**						**Mean**
	mass [kg]	4	4	4	7.3	7.3	7.3	[%]
	height [cm]	5	10	20	5	10	20	
Infilled turf surfaces								
1		87.5	87.4	84	80.8	84.8	80.2	84.1
2		83.8	83.6	83	87.4	86.3	86.7	85.1
Point elastic surfaces								
1		80.1	77.1	77.1	73.8	72.4	76.3	76.1
2		80.1	72.4	75.5	75.5	71.2	77.1	75.3
3		78.6	74.8	76.3	72.0	69.9	76.3	74.6
4		68.4	64.6	70.3	68.4	64.5	69.4	67.6
5		70.3	64.6	68.5	64.5	63.1	62.7	65.6
6		58.6	60.3	63.7	62.6	61.7	66.1	62.2
7		58.6	52.5	55.3	49.6	47.6	53.1	52.8
8		58.6	49.3	51.9	51.9	45.9	48.4	51.0
9		51.9	44.2	49.6	44.8	40.7	44.8	46.0
10		49.6	40.6	46.0	44.8	40.6	42.3	44.0

The energy returned from the point elastic surfaces was higher than the infilled surfaces. There were large differences, however, between the point elastic surfaces although they were all constructed for installation as a competitive running track. The differences in energy return of the tested surfaces were substantial and it may be that these differences affect performance of the athlete. For this particular group of point elastic surfaces, the amount of energy returned from the surfaces increased as surface thickness increased. It may be that some surface samples were not thick enough to absorb and return the maximal amount of energy. Although energy return is not directly related to surface thickness, if the surface bottoms out upon impact it loses a lot of energy which would be stored and possibly returned if the material was thicker.

The absolute magnitude of energy loss measured during mechanical drop tests must be interpreted cautiously (Nigg and Yeadon, 1987). As can be seen in Table 2, the magnitude of energy loss is somewhat dependent on dropping mass and height and is also known to depend on the shape of the dropping mass. Both mechanical tests (Cavanagh et al., 1980; Luethi et al., 1985) and subject tests (Bowers et al., 1974; Andreasson et al., 1983; Junqua et al., 1983) have been used to try to quantify energy return of sport surfaces. However, the correlation between the two methods is often low (Nigg and Yeadon, 1987). In fact, the energy lost during mechanical drop tests may overestimate the energy lost during actual sport activities. Using a finite element model with actual ground reaction forces during running as input parameters, Baroud et al. (1999a) estimated the energy loss in a typical running surface is only 1-2%. They suggest that quick impacts during the mechanical tests do not allow the surface to respond quickly enough, whereas the longer stance times provide sufficient time for the surface to almost fully expand to its original thickness. Unfortunately, no current experimental values during actual sporting activities are available to support or refute this claim.

Surface vibrations are another aspect that can lead to energy loss (Nigg and Anton, 1994). Vibrations are most apparent on stiffer area elastic surfaces. Figure 2 shows the vibrations of a hardwood floor following the landing of an athlete and the impact of a basketball. Since the energy remained in the vibrating surface, it was not returned to the athlete (or ball) and was eventually lost.

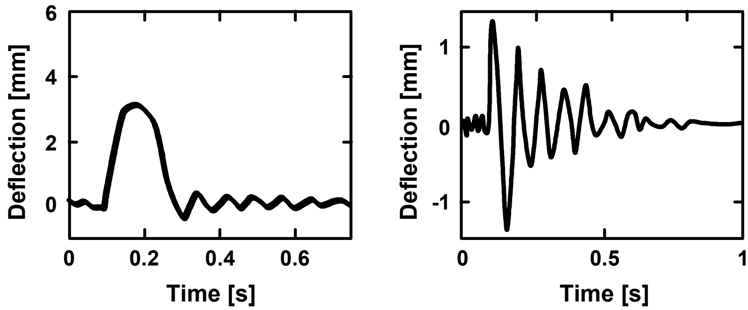

Fig. 2. Deformation of a hardwood surface after contact by an athlete during a drop jump (left) and a basketball bounced on the surface (right). Note the vibrations that occur on the surface after contact. (adapted from de Koning et al., 1997).

Energy return

Energy return is only relevant if the magnitude is large enough to have an influence on performance. As was shown in the previous section, about 15-60% of the energy that is input into typical sport surfaces is returned. However, these magnitudes are in many cases substantial enough to influence athletic performance. It has been estimated that the mechanical energy required for a forefoot running stride is 182 J (Baroud et al., accepted). A storage of 12J of energy in a running track (Table 1) represents about 6.5% of the energy required. Even if 50% of the energy is lost, a return of 6J is still substantial representing over 3% of the mechanical energy per stride. If all of this energy returned aids performance, a 3% increase in performance relates to about 0.3 seconds in an elite level 100m race. This description is an oversimplification and it is unlikely that all of the returned energy goes directly into athletic performance, however, it demonstrates the importance of energy return from sport surfaces.

Although energy is a scalar quantity, that is, it is defined by its magnitude and it is independent of direction, the forces that are exerted by a surface as energy is returned are vector quantities, having both magnitude and direction. Therefore, for an athlete to make effective use of the returned energy, the forces from the surface must be exerted at the right location, in the proper direction, at the appropriate time and with the right frequency (Nigg and Segesser, 1988).

For energy to be returned at the right location, it should be returned at the location of the athlete at take-off. A good example is a gymnastics surface. The athlete compresses the surface and remains in the same position as the surface returns to its original uncompressed state. In contrast, energy return at the right location is more difficult on a running surface. During running, an athlete lands with their heel, compressing a certain spot on the surface. They then roll onto the forefoot for take-off. Their point of contact has now shifted forward on the surface and the location where the energy was stored is no longer the location where the athlete requires the energy to be returned. Thus certain surfaces are inherently more capable of returning energy at the right location due to the nature of the sport.

During a vertical jump, it is important that the force exerted on the athlete is primarily vertical to make effective use of the energy stored. During a running stride or a side-cut movement, the primary goal is to move horizontally so it is important for a large component of the force to be directed horizontally. This is particularly difficult during running as the initial force during landing, when energy is stored, is in the anterior direction. As a result, a standard running surface will exert an expansion force in the posterior direction. However, during take-off the athlete requires a force in the anterior direction to aid their performance, exactly opposite to what may be occurring. Therefore, the direction that the surface exerts force is important for appropriately utilizing the stored energy.

The timing of energy return is important. Energy is wasted if it is returned at a point in time that the athlete can not benefit from it. In most movements, energy should be stored during approximately the first 50% of ground contact and returned during the second 50%. This may appear elementary, however, there are some instances, such as running again, where some energy return occurs too early and is not beneficial to the athlete (Stefanyshyn and Nigg, 2000b).

If energy is stored during approximately the first half of ground contact and returned during the second half, the deformation and release correspond roughly to one half of a sinus wave. The loaded natural frequency of the surface should be matched to the frequency of the activity to maximize the utilization of the energy returned. For example, sprinters contact the surface for about 0.10 s (Fig. 3). One full cycle then corresponds to 0.20 s, or a frequency of 5 Hz. Optimal sprinting surfaces should, therefore, have loaded natural frequencies around 5 Hz. The natural frequency of a system or piece of equipment is dependent on the mass and the stiffness of the system. Increasing the stiffness increases the frequency while increasing the mass decreases the frequency. Since the mass of the athlete on the surface is given, the frequency of the surface can be modified by changing the stiffness of the surface.

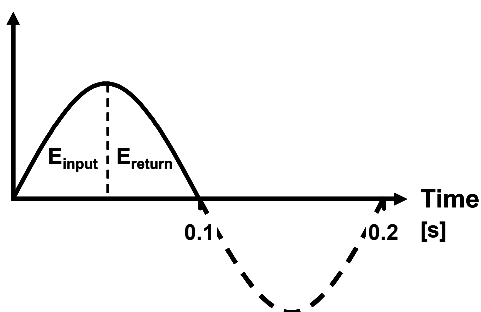

Fig. 3 Schematic representation of the surface deformation during ground contact of a sprinting stride. A contact time of 0.1 s corresponds to a loading and unloading frequency of 5 Hz.

Energy return in sport surfaces

Gymnastics floors

As was seen in Table 1, tumbling and gymnastics surfaces have the potential to store large amounts of energy. The springy surfaces are specially designed to store and return energy to the athletes. Energy return values of 150 J (Table 1) would allow an average 60 kg gymnast to jump 25 cm higher and remain in the air over 0.2 s longer. The additional energy allows for higher jump heights and longer flight phases so that the gymnasts can perform impressive maneuvers that simply would not be possible on other surfaces.

Running tracks

McMahon and Greene (1978, 1979) studied track surfaces with different compliance and showed that there is an optimal stiffness that maximizes energy return and performance. Using a theoretical model, they predicted that the athletes would be fastest on an infinitely stiff surface without any deformation. However, this was only true if the runner was modeled as an ideal elastic system without any damping. When the runner was modeled with internal damping and energy dissipation, more representative of reality, their model suggested an intermediate stiffness would maximize the energy return and running speed. This optimal stiffness was determined to be approximately 160 – 320 kN/m and the model predicted a 1-3 % increase in running speed at these stiffnesses. Based on these results, a new running track was constructed at Harvard University with a stiffness of approximately 240 kN/m. Experimental results on this track verified the model predictions as speed enhancements of approximately 2 % were realized, a dramatic increase in performance.

Structured surfaces

Conventional running surfaces are typically solid multi-layer configurations made of rubber. Such a construction has only a limited capacity to deform. However, the capacity to deform, and consequently to store and return elastic energy, could potentially be increased dramatically by developing a structured sport surface. Furthermore, current isotropic and homogenous sport surfaces allow equal deformation in all directions. However, many athletic activities such as sprinting and running competitions always occur in the same direction. Thus, energy return and the direction of the returning force can be modified by implementing a structured surface, which in turn may have a direct influence on performance. Therefore, an investigation was undertaken to determine if structural surfaces have increased potential in returning energy under actual loading conditions exerted during stance in running (Baroud et al., 1999b; Stefanyshyn et al., 2001).

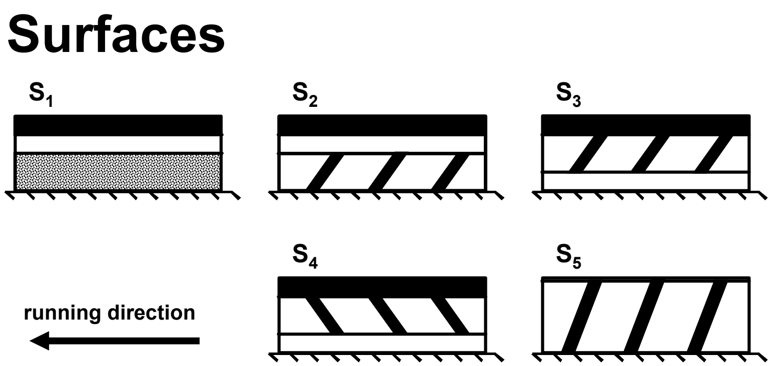

Fig. 4. Surface configurations used for a finite element analysis on energy return. S_1 represents a typical three layer construction. S_2-S_5 depict different structural constructions varying in layer placement as well as thickness and direction of the structural components.

The study was performed using a finite element analysis. A conventional three-layered solid surface was compared to four structural surfaces of various construction (Fig. 4). The structured surfaces consisted of solid top and/or bottom layers with diagonal supports. All surfaces were 20 mm thick and had the same material properties, which were represented by a visco-elastic constitutive model. The material properties were determined experimentally on a conventional surface using uni-axial relaxation and compression experiments (Rens et al., 1994). Ground reaction forces measured during forefoot running were used as input data in the study. Energy input, energy lost and energy returned were determined by the line integral of the external forces and the displacements along the loading and unloading curves.

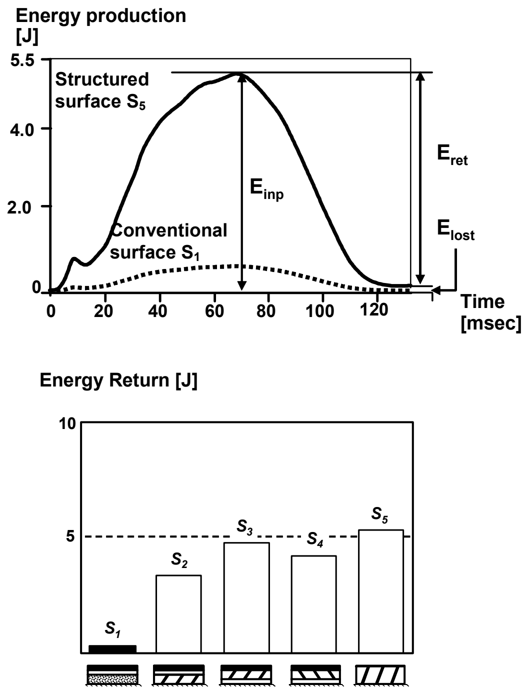

Fig. 5. Energy input and energy returned as a function of time for a conventional homogeneous and a structured surface (left). The magnitude of energy returned for the five different surfaces (right).

The structured surfaces had over a ten-fold increase in the amount of energy returned to the athlete when compared to the conventional surface (Fig. 5), despite the fact that all surfaces were constructed with the same material properties and the same thickness. The reduced stiffness of the structured surfaces allowed substantially larger deformations, resulting in larger amounts of energy being both input into and returned by the surface. Also, the direction of the structured surface had an influence on the amount of energy returned. For example, two of the directional surfaces (S_3 and S_4) were identical except for the orientation of the structural elements within the construction.

By modifying the direction of the structural elements, differences of up to 10% in the returned energy were seen. Changing direction of the structural elements influences the directional stiffness of the surface. The surface is no longer homogenous but rather is stiffer in one direction than another. Since the forces applied during running are directional, this directionality can be exploited to maximize energy return. Figure 6 shows how a surface can be relatively stiff in one direction but more compliant in another direction. The directionality of the structural elements also allows forces to be applied from the surface to the athlete in the right direction, the direction they are running.

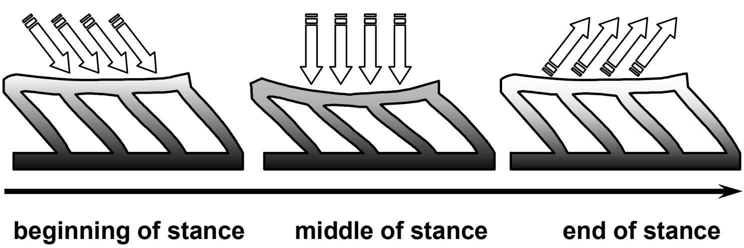

Fig. 6. Schematic showing the relationship between force and deformation of a structural surface during a running stride. As an athlete lands, forces are applied in the direction that the surface is most stiff, therefore, deforming very little. The surface is more compliant and deforms more during midstance allowing it to store energy. During take-off, the surface returns to its original shape and applies forces on the athlete in the running direction.

It has been estimated that a running stride requires about 180 J of mechanical energy (Baroud et al., accepted). If it is assumed that energy production is directly related to performance, structural surfaces have the potential of improving performance by approximately 2.5%. However, these improvements are going to depend on factors such as timing and frequency characteristics and should be verified experimentally.

References

Andreasson, G. and Olofsson, B. (1983) Surface and shoe deformation in sport activity and injuries. In Biomechanical Aspect of Sport Shoes and Playing Surfaces (eds. Nigg, B.M. and Kerr, B.A.) University Printing, Calgary, AB, Canada. pp51-61.

Baroud, G., Nigg, B.M. and Stefanyshyn, D.J. (accepted) Energy return and performance enhancement in sport surface consideration of viscoelastic material properties. Journal of Applied Biomechanics.

Baroud, G., Nigg, B.M. and Stefanyshyn, D. (1999a) Energy storage and return in sport surfaces, Sports Engineering, 2, 173-180.

Baroud, G., Nigg, B.M. and Stefanyshyn, D.J. (1999b) Can athletic performance be enhanced by sport surfaces and sport shoes? Proceedings of the International Society of Biomechanics XVIIth Congress, 237.

Bowers, K.D. and Martin, R.B. (1974) Impact absorption, new and old turf at west Virginia university. Medicine and Science in Sports and Exercise, 6, 217-221.

Cavanagh, P.R. and Lafortune, M.A (1980) Ground reaction force in distance running. Journal of Biomechanics, 13, 397-406.

De Koning, J.J, Nigg, B.M. and Gerritsen, K.G (1997) Assessment of the mechanical properties of area elastic sport surfaces with video analysis. Medicine and Science in Sports and Exercise, 29, 1664-1668.

Junqua, A., Pavis, B., Lacouture, P., Nviere, J. and Rivat, A (1983) About standards on sport floors. In Biomechanical Aspect of Sport Shoes and Playing

Surfaces (eds. Nigg, B.M. and Kerr, B.A.) University Printing, Calgary, AB, Canada. Pp77-82.
Luethi, S.M., Denoth, J., Kaelin, X., Stacoff, A. and Stuessi, E. (1985) The influence of the shoe on foot movement and shock attenuation in running In: Abstract Book, 10th International Congress of Biomechanics, Vetenskaplig Skriftserie, Umea, Sweden, p. 164.
McMahon, T.A. and Greene, P.R.: Fast running tracks. Scientific American, 239 (1978) 112-121.
McMahon, T.A. and Greene, P.R. (1979). The influence of track compliance on running. Journal of Biomechanics, 12 893-904.
Nigg, B.M. (1999) Force. In Biomechanics of the Musculoskeletal System (eds Nigg, B.M. and Herzog, W.) John Wiley and Sons, New York, NY. pp 261-287.
Nigg, B.M. and Yeadon, M.R. (1987) Biomechanical aspects of playing surfaces. Journal of Sports Sciences, 5, 117-145.
Nigg, B.M. and Segesser, B. (1992) Biomechanical and orthopedic concepts in sport shoe construction. Medicine and Science in Sports and Exercise, 24, 595-602.
Nigg, B.M. and Anton, M.: Energy aspects for elastic and viscous shoe soles and playing surfaces. Medicine and Science in Sports and Exercise, 27 (1995) 92-97.
Nigg, B.M., Stefanyshyn, D.J. and Denoth, J 2000: Work and energy – mechanical considerations. In International Handbook of Sport Science, Biomechanics and Biology of Human Movement. Edited by Nigg, B.M., MacIntosh, B.R. and Mester, J.A. Human Kinetics Publishers, Champaign, Ill. pp 5-17.
Rens, B.J.E. van,et al. WFW-rapport 94.151, Technische Universiteit Eindhoven, 1994.
Passmore, R. and Durnin, J.V. (1955) Human energy expenditure. Physiological Reviews, 35, 801-836.
Stefanyshyn, D.J. and Nigg, B.M. (2000a) In International Handbook of Sport Science, Biomechanics and Biology of Human Movement. Edited by Nigg, B.M., MacIntosh, B.R. and Mester, J.A., Human Kinetics

Publishers, Champaign, Ill. pp 49-66.
Stefanyshyn, D.J. and Nigg, B.M. (2000b) Energy aspects associated with sport shoes. Sportverletzung-Sportschaden, 14, 82-89.
Stefanyshyn, D.J., Baroud, G. and Nigg, B.M. (2001) The potential of structured surfaces. Book of Abstracts of the 6th Annual Congress of the European College of Sport Science, 90.
Strydom, N.B.Bredell, G.A., Benade, A.J., Morrison, J.F., Vijoen, J.H. and van Graan, C.H. (1966) The metabolic cost of marching at 3 mph over firm and sandy surfaces. Internationale Zeitschrift fur Angewandete Physiologie Einschlieslich Arbeitsphysiology, 23, 166-170.