Energy Cost and Pole Forces during Nordic Walking under Different Surface Conditions

THORSTEN SCHIFFER, AXEL KNICKER, REGINE DANNÖHL, and HEIKO K. STRÜDER

Institute of Motor Control and Movement Technique, German Sport University Cologne, Cologne, GERMANY

ABSTRACT

SCHIFFER, T., A. KNICKER, R. DANNÖHL, and H. K. STRÜDER. Energy Cost and Pole Forces during Nordic Walking under Different Surface Conditions. *Med. Sci. Sports Exerc.*, Vol. 41, No. 3, pp. 663–668, 2009. **Introduction**: The purpose of the study was to identify the effect of three different surfaces on energy consumption and the forces acting on the walking poles during ground contact in Nordic walking (NW). **Methods**: Thirteen female NW instructors (age = 26 ± 4 yr, weight = 58.5 ± 4.2 kg, height = 168.1 ± 4.6 cm) volunteered in the study. The subjects walked a distance of 1200 m at a controlled, constant speed of 2.2 $m \cdot s^{-1}$ on each of a concrete surface (C), an artificial athletics track (A), and a naturally grown soccer lawn (G). They used NW poles with inbuilt strain gauge force transducers to measure ground reaction forces acting along the long axes of the poles. Oxygen uptake, capillary blood lactate (La), HR, and RPE were measured before and after the tests. **Results**: Impact forces, maximum forces, force rates during ground contact identified from the registered force time histories, displayed significant differences related to the surface conditions. However, force time integrals did not show surface-related differences. Relative oxygen consumption showed significant differences between NW on C and on G whereas no surface-related differences could be identified between the surface conditions for the parameters La, HR, and RPE. **Conclusion**: Our data indicate that the impulse that is generated by the poles on the subjects is identical between the varying surfaces. Because there are differences for the oxygen uptake between C and G, the main regulator for the propulsion must be the musculature of the lower extremities. The work of the upper extremities seems to be a luxury effort for Nordic walkers with a proper technique.

Key Words: POLE REACTION FORCES, PROPULSION, OXYGEN UPTAKE, LACTATE

Regular participation in endurance sports with moderate intensities and high caloric expenditure is known to maintain or improve health (1,11). Nordic walking (NW) is still a growing discipline among endurance sports, which is widely used in health and leisure time sports. The use of poles leads to increased HR, oxygen uptake ($\dot{V}O_2$), and capillary blood lactate (La) values compared with walking (5,17,18,20). The increased metabolic and cardiovascular demands with NW are often explained by the additional use of the upper-body musculature, which is necessary for executing the poling technique properly. There exists neither data about the amount of the generated forces nor about the contribution of the upper-body musculature for the propulsion by the poles.

In addition to specific demands of endurance disciplines (6,20,23), the energy cost for a standardized bipedal work depends on the mechanical properties of the surface (9,12,16,22,26). The causal for different energy costs (9,12) and the amount of mechanical impact absorption (7) of bipedal locomotion on different surfaces are the energy-absorbing property of the surface. Causal for different energy costs of running on different surfaces is the energy-absorbing property of the surface (7,16). Hardin et al. (9) compared three different stiffness settings of the surface on a treadmill, ranging from 100 to 350 $kN \cdot m^{-1}$. They have shown that an increase of the surface stiffness reduces oxygen demands and vice versa. The comparison of the energy costs for running in a natural environment, that is to say sand versus grass, resulted in significant greater energy costs on sand (16). Similar with the described data for running, Lejeune et al. (12) measured up to 2.7 times higher energy expenditure for walking on soft compared with hard surfaces. Most studies about NW (5,17,18,20) measured increased energy demands compared with walking at standardized movement speeds and on standardized surfaces. Although NW is an outdoor discipline, these studies were executed on tread mills or artificial tracks, which do not resemble conditions occurring in the Nordic walkers' natural environment. Due to the similarities of the bipedal locomotion styles, we hypothesized that the energy expenditure for NW on different surfaces varies equivalent to the stiffness of the surface.

The effect of the use of poles on propulsion is still not revealed. Willson et al. (24) reported increased self-selected walking speed with poles compared with walking without poles and decreased stress on knee and ankle joints resulting from the forces during shoe–ground contact.

Address for correspondence: Thorsten Schiffer, M.D., Ph.D., Institute of Motor Control and Movement Technique, German Sport University Cologne, Carl-Diem-Weg 6, 50933 Cologne, Germany; E-mail: t.schiffer@dshs-koeln.de.

Submitted for publication February 2008.
Accepted for publication August 2008.

0195-9131/09/4103-0663/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e31818b9321

APPLIED SCIENCES

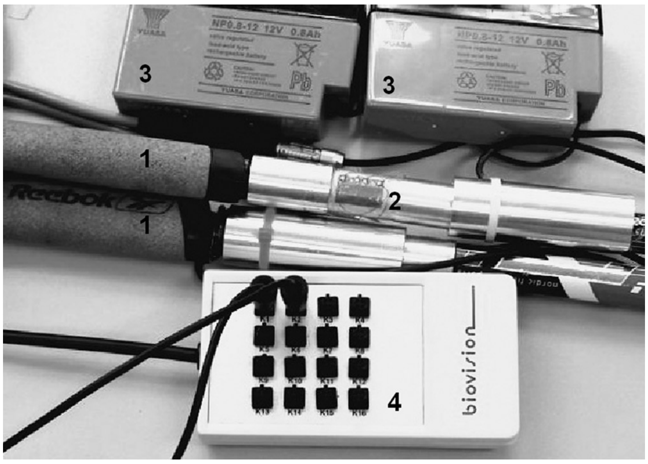

FIGURE 1—Walking poles (1) with force transducer (2), battery packs (3), and AD conversion box (4).

Kleindienst et al. (10) revealed higher vertical and horizontal ground reaction forces during landing for NW compared with walking but significantly lower forces during push off. Forces transmitted through the poles remained undetermined in both studies. The results of the studies lead to differently weighted conclusions about the load situation during NW. Kleindienst et al. (10) doubt that reduced vertical ground reaction forces during push off alone lead to lower mechanical loads, whereas Willson et al. (24) concluded that reduced average ground reaction forces during foot ground contact during NW compared with normal walking lead to less lower extremity loading.

Surface conditions contribute considerably to oxygen consumption. The more energy is dissipated by the surface, the more effort and energy will be required to maintain locomotion speed. Under the assumption that the use of the poles contributes to the overall propulsion, we suppose that depending on the mechanical properties of different surfaces also, pole reaction force parameters, such as maximum force applied to the pole to maintain its contribution to gross propulsion force rate as a measure of the load transferred to the locomotor system, contact duration will show surface-type–specific parameter patterns during NW at a controlled walking speed.

METHODS

Subjects. Thirteen women with an average age, body mass, and height of 26 (SD = 4) yr, 58.5 (SD = 4.2) kg, and 168.1 (SD = 4.6) cm, respectively, participated in this study. All participants were experienced in NW on an instructor level and were familiar with the use of NW poles. Before the beginning of the study, all subjects completed medical examination and physical activity questionnaires and signed a written consent form. The study was approved by the local ethics committee.

Experimental procedure and protocols. Each subject completed one 18-min field test consisting of three 1200-m units each on an artificial track, grass and concrete in the track and field arena of the German Sport University Cologne. The order of the surfaces was chosen randomly. The NW speed was given with 2.2 $m \cdot s^{-1}$. To provide a constant speed, we used pylons, which were placed every 50 m on the track. An electronic time transmitter provided an acoustic signal with constant delay time every 50 m, which was adjusted to the necessary speed. Food intake was standardized 2 d before the test, and all participants were not allowed to be physically active the day before the test.

Measurements and analysis. Capillary blood lactate (La) was analyzed from the earlobe (BIOSEN C line, EKF-diagnostic GmbH, Barleben, Germany) at the end of every unit. After executing the calibration as described by the manufacturer, oxygen uptake ($\dot{V}O_2$) was continuously measured with a portable indirect calorimetry system ($K4b^2$, Version 7.4b, Cosmed, Rome, Italy). HR was recorded continuously with Polar Vantage XL (Polar Electro, Kempele, Finland). Data for HR and $\dot{V}O_2$ from the last 30 s of every unit were analyzed with the corresponding software.

To measure the forces acting along the longitudinal axes of the poles directly and over a representative number of strides, a strain gauge force transducer has been built into each of the walking poles (Fig. 1). Four strain gauges operating as half bridge circuits were glued to an aluminum tube, which was tightly mounted into the tube of the poles as close as possible to the handgrips. The strain gauges were calibrated in a Z-020 Zwick material tester (Zwick Roell AG, Ulm, Germany). The output signal was amplified so that the change of the output voltage of 1 V was equivalent to a change in force application of 50 N. Linearity was below 1%.

The output signal was transferred by wire to a data logger System (Biovision, Wehrheim, Germany) consisting of a pocket PC (HP 5450, HP Inc., Houston, TX) holding a DAQP-12 32-bit AD conversion card (Quatech Inc., Hudson, OH) and stored in ASCII format using PLAB data

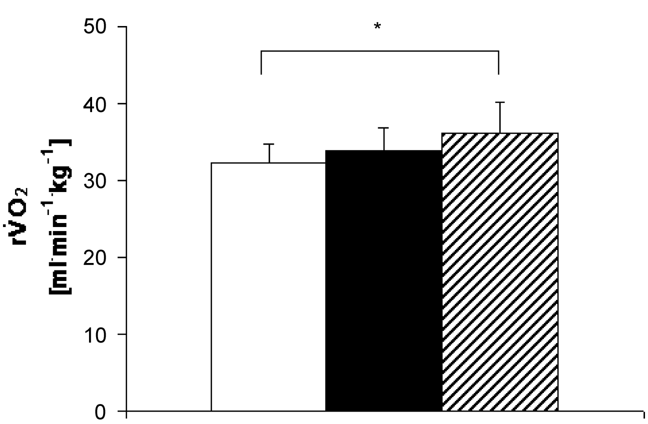

FIGURE 2—Relative oxygen consumption (mean ± SEM) during the field tests on concrete □, artificial track ■, and grass ▨ at a constant speed of 2.2 $m \cdot s^{-1}$. NW on concrete is significantly different (*$P < 0.05$) compared NW on grass.

acquisition software (Stiegele Datasystems, Rothenburg o.d.T. Germany). Pocket PC and power supply for the force transducers had to be carried by the subjects in a small backpack (weight <1 kg).

Surface properties. Information about the mechanical properties in principal of the surface types used in this study was provided by the manufacturer of the artificial track (Polytan Inc., Halle, Germany). The values given below are based on data of a device known as artificial athlete 95 (Institute for Sport Surface Technology, Markkleeberg, Germany), which quantifies the energy dissipation of the surface in vertical direction. Force reduction values for the three surfaces were

1. concrete (C): 5%;
2. artificial track (A): 39%; and
3. grass (G): 50%.

Statistics. Statistical evaluation was carried out with SPSS (Version 13.0 for MAC OSX; SPSS Inc., Chicago, IL). Repeated-measures ANOVA was used to assess statistical differences between parameter patterns in regard to the surface conditions. Duncan *post hoc* test for homogenous variances and Tamhane-T2 test for inhomogeneous variances were applied for multiple comparisons. Data are expressed as mean ± SD. The significance level for all analyses was set at $P \leq 0.05$.

RESULTS

NW on G resulted in significantly higher relative $\dot{V}O_2$ (Fig. 2) and MET (Table 1) compared with C ($P < 0.05$). $\dot{V}O_2$ on A (33.8 ± 3.1 $mL \cdot min^{-1} \cdot kg^{-1}$) was not significant different compared with the highest $\dot{V}O_2$ on G (36.1 ± 4.2 $mL \cdot min^{-1} \cdot kg^{-1}$) and the lowest $\dot{V}O_2$ on C (32.1 ± 2.5 $mL \cdot min^{-1} \cdot kg^{-1}$). HR, minute ventilation, breathing frequency, La, and RPE were not influenced by the type of the surface (Table 1).

Axial forces were in the range of 9.7–68.1 N with a mean of 36.5 ± 14.5 N for C, 12.9–79.3 N with a mean of 41.8 ± 14.6 N for A, and 12.9–74.1 N with a mean of 43.3 ± 13.7 N for G. The force time histories showed a three-peak characteristics with the first peak representing the initial impact of the poles' tip on the ground, the second and largest peak representing the initial push, and the third peak can be attributed to the final push before pole takeoff (Fig. 3), which accompanies the push off action of the contralateral foot.

TABLE 1. MET, HR, RPE, and capillary blood lactate (La) during NW on concrete, artificial track, and grass.

	Concrete	Artificial Track	Grass
HR (bpm)	162 ± 16	169 ± 21	173 ± 20
RPE	12 ± 2	11 ± 2	13 ± 2
Lactate ($mmol \cdot L^{-1}$)	2 ± 0.6	2.3 ± 1	2.5 ± 1
MET	9.1 ± 0.7*	9.6 ± 0.9	10.2 ± 1.2*

Data are presented as mean ± SEM.
* Significantly different between concrete and grass ($P < 0.05$).

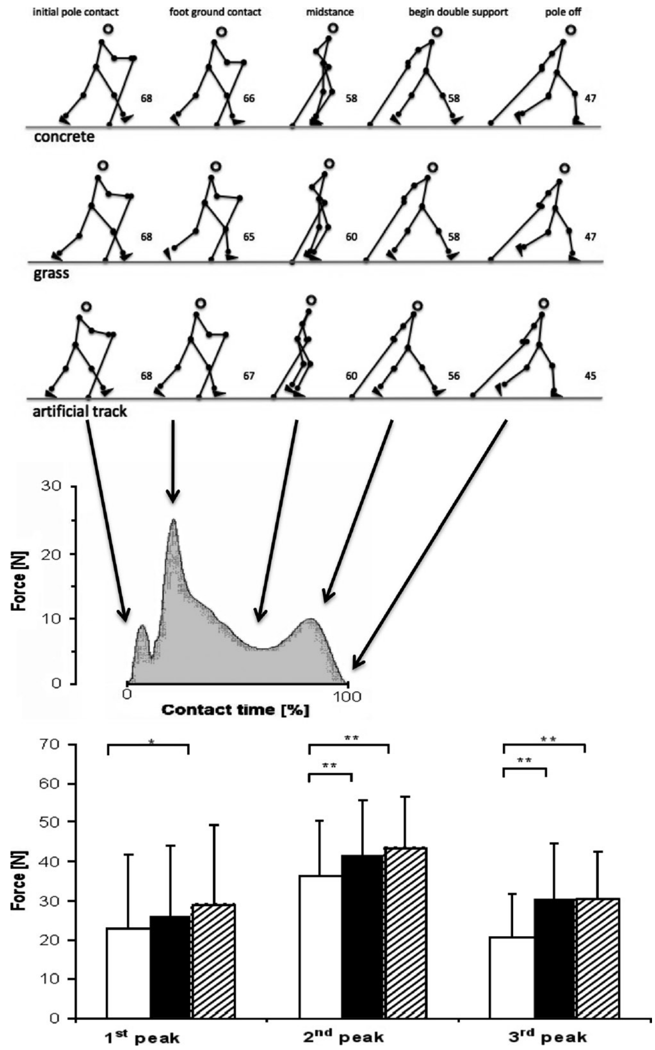

FIGURE 3—(*Top*) Stick figure representation of one pole ground contact phase assigned to a typical force–time history of pole reaction forces; numbers given to the right of each stick figure estimate the inclination of the poles relative to the ground. (*Bottom*) Forces (mean ± SEM) at the force peaks on concrete □, artificial track ■, and grass ▨ at a constant speed of 2.2 $m \cdot s^{-1}$. Forces are significantly lower on concrete compared with grass (*$P < 0.05$, **$P < 0.01$).

In line with the significant differences of the axial forces at the three peaks, there were significant higher average force rates for G compared with C at the first ($P < 0.05$) and the second peak ($P < 0.01$; Fig. 4, Table 2).

There were no changes for the force impulses transferred to the ground with the poles between the surfaces (C: 7.1 ± 3.1 N·s; A: 7.7 ± 2.8 N·s; G: 7.5 ± 2.5 N·s), whereas the contact time of the poles on the ground was inversely measured compared with the parameters force rate and axial force with shortest contact times on G (0.36 ± 0.04 s) and longest contact times on C (0.38 s ± 0.06 s; $P < 0.05$; Fig. 4).

DISCUSSION

$\dot{V}O_2$, La, and HR. Independent from the surface conditions, the values of the current study for $\dot{V}O_2$ (32–34 $mL \cdot kg^{-1} \cdot min^{-1}$) and HR (162–173 bpm) were higher

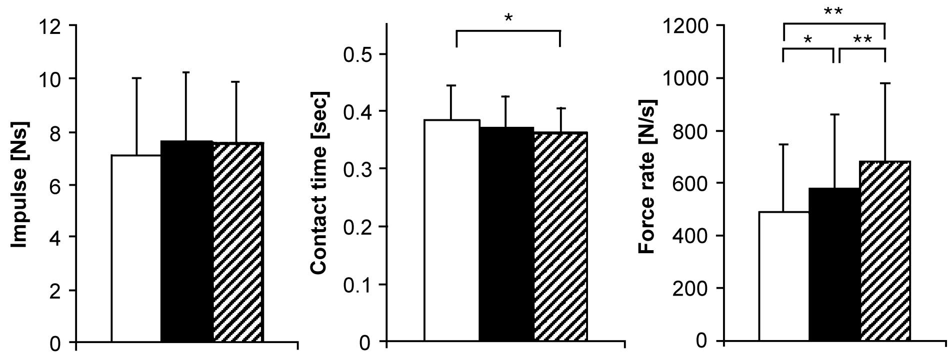

FIGURE 4—Impulse and contact time of the poles and maximal force rate at the second peak (mean ± SEM) on concrete □, artificial track ■, and grass ▨ at a constant speed of 2.2 m·s^{-1}. Contact time is significantly lower on grass compared with concrete (*P < 0.05). Highest force rates on grass (P < 0.01).**

compared with results from other studies (5,18,20). This discrepancy can be explained by the selection of our subjects because well-trained athletes possess optimal adaptations to their specific aerobic exercise so that they are able to perform their submaximal exercise with less oxygen demand compared with novices (2,13). Thus, our subjects were able to perform at a relatively high movement speed of 2.2 m·s^{-1} still working at a submaximal intensity. This speed is close to the transition from walking to running (1.8–2.5 m·s^{-1}), for which we assumed a leveling effect for NW (20), which is debated to be responsible for an inefficient poling technique compared with slower movement speeds (5,20). However, relatively low La values (2–2.5 mmol·L^{-1}) in this study compared with approximately 5 mmol·L^{-1} La at 2.1 m·s^{-1} (20) and the moderate ranking on the scale of perceived exertion (3) between 11 and 13 indicate that our subjects were able to exercise at high NW velocities without reaching the intensities that are known to have negative effects on a proper NW technique.

Higher values for relative $\dot{V}O_2$ during NW were registered at a constant speed of 2.2 m·s^{-1} on G compared with C (P < 0.05). These data are in accordance with results from Hardin et al. (9), who measured highest oxygen consumption on soft surface and vice versa for runners on a treadmill. Based on their kinematic measurements, they concluded that harder surfaces resulted in lower leg stiffness that appeared to minimize the oxygen consumption. Although we measured no differences for the oxygen consumption between NW and running at a speed of 1.8 and 2.1 m·s^{-1} on a tartan track (20), the transfer of these explanations from running on a treadmill to the results of the current study would be inaccurate. There exist marked differences between the used surfaces and the energetic mechanisms for the bipedal disciplines running and walking. Running uses predominantly elastic energy by a bouncing mechanism, whereas walking generates its energy mainly from a pendulum mechanism with a continuous exchange of kinetic and potential energy (4,19). The experimental change of the surface stiffness of a treadmill belt as accomplished by Hardin et al. (9) was based on variations of the treadmill belts' area elasticity, which cannot be compared directly to the predominantly point elastic nature of concrete and grass in our study. Lejeune et al. (12) demonstrated that a 2.1–2.7 times increase of energy expenditure for walking on sand compared with a hard surface at the same speed is due to an increased external mechanical work, whereas the increased energy expenditure for running originates in decreased muscle-tendon efficiency. Similar results with 1.8 times higher energy costs for walking on sand compared with compact terrain were measured by Zamparo et al. (26). Soule and Goldman (22) developed a coefficient for the prediction of energy costs of walking on different terrains. Our data revealed that oxygen consumption during NW on soft and hard surfaces is basically in correspondence with the prediction of energy costs derived from walking on black top surface and light brush (22) and the presented data for running and walking on varying surfaces (9,12,16,22,26). However, the exact underlying biomechanical and kinetic mechanisms remain unclear.

Mechanical load and propulsion transferred in axial direction of the walking poles. The measurements of the mechanical effects of the three sport surfaces used in the present study on pole reaction forces were inversely related to the vertical impact-absorbing ability as tested with an artificial athlete (see Methods). Maximum reaction force parameters measured during pole ground contact represent the load transferred through the poles to the musculoskeletal system of the upper body. The poles can be looked upon as the interface between the upper body's extremities and the ground. The force–time history of the pole reaction force describes three peaks during the contact time of the poles on the ground (Fig. 3). Pole reaction forces were higher on soft surfaces (G) compared

TABLE 2. Force rate at the first peak and the second peak during NW on concrete, artificial track, and grass.

	Concrete	Artificial Track	Grass
Force rate first peak (N·s^{-1})	958 ± 780*	1028 ± 793	1255 ± 931*
Force rate second peak (N·s^{-1})	487 ± 257†	577 ± 280	678 ± 304†

Data are presented as mean ± SEM.
* Significant between concrete and grass (P < 0.05).
†Significant between concrete and grass (P < 0.01).

with stiff surfaces (C) at all three peaks (P1: $P < 0.05$; P2 and P3: $P < 0.01$). The higher forces applied to the poles on grass can be regarded as a direct effect of the force reduction properties of the surface, which the subjects try to overcome by putting more effort into the push from the poles. This can be due to a better balance control or due to the subjects' desire to push stronger to support the overall propulsion.

With the exception of the force rate related to the second force peak, no significant differences could be identified for any of the force parameters between A and G. Although force reduction properties for A and G are 8–10 times higher than for C (see Methods), force time characteristics as measured along the long axes of the poles do not reflect the mechanical surface properties. The dimension of the differences between, for example, the second peak forces lies in a range between 5 and 7 N, which is about 1% of the subjects' body weight. Thus, the differences identified do not reveal considerable load situations.

The impulse represents the propulsion effect of the use of the poles although we cannot differentiate between directions of force application. The fact that the impulses resulting from pole ground contact are not statistically different although vertical maximal forces are different between C and G indicates that the use of the poles does not contribute to whole body propulsion. This result confirms the findings of Kleindienst et al. (10). The extent of the impulse by the upper-body musculature on the subjects consists of the product of vertical force and contact time. In this study, the reciprocal relation between the contact time and the vertical force with shorter contact times of the poles on the ground on G compared with C ($P < 0.05$) may explain the lack of effects on the impulse. Pole inclination derived from qualitative movement analysis starts from about 70° at initial pole contact and 45° (Fig. 3) at terminal pole off during pole ground contact. Thus, between one third (at pole plant) and two third (push off) of the axial forces and the resulting impulses are applied in a horizontal direction and have the potential to add momentum to forward propulsion. The average impulse registered in this study was about 7.5 N·s. Thus, the horizontal aspects are in the range of 2.5 and 5 N·s. As we cannot assume that the resulting momentum can be transferred without loss to the center of gravity the effects of poling action on overall propulsion is only marginal.

The rate of force development is an estimate for the effort of pole plant. The slope of the maximum force rate at P2 was significantly different between all conditions ($P < 0.01$ between C and G and between G and A, and $P < 0.05$ between C and A). Softer surfaces like G seem to facilitate a more explosive movement pattern compared with stiffer undergrounds. Due to the cushioning properties of the surfaces, we would have expected highest force rates on C. This discrepancy might be explained by neurosensitive proprioceptive adaptations on varying environmental conditions, which is known from studies regarding gait and stance abilities of humans on altered underground conditions including vibration, footwear, and grip (9,15,21). Thus, our data might reflect an unconscious mechanism, which down-regulates the developed force rate by the skeletal muscle on stiff surfaces and thus serving to avoid stress on the passive structures of the upper extremities. Similar internal neurosensitive principals are discussed for the prevention of injuries of the lower extremities while running on stiff surfaces (9,14,25).

CONCLUSIONS

Since the impulse, which is generated by the poles on the body, is identical between the varying surfaces and there are differences for the $\dot{V}O_2$ between C and G, the main regulator for the propulsion must be the musculature of the lower extremities. The work of the upper extremities seems to be a luxury effort for Nordic walkers; with a proper technique, it might also include a balance control mechanism rather than an active contribution to forward propulsion. Our data regarding the pole reaction forces therefore do not reflect findings about the load of lower extremities of Dixon et al. (7) who measured the greatest amount of mechanical impact absorption on soft surfaces for the lower extremities. On the other hand, Glasheen and McMahon (8) showed that metabolic costs and force generation are due to differing stiffness abilities of the upper and the lower extremities four to five times higher for running on arms compared with running on limbs of running quadrupeds. Thus, results from lower extremities must not be transferred directly onto the upper extremities due to marked structural differences of the limbs.

We thank the subjects who devoted time and effort to the study.
The results of the present study do not constitute endorsement by ACSM.

APPLIED SCIENCES

REFERENCES

1. American College of Sports Medicine. Position Stand. The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. *Med Sci Sports Exerc*. 1998;30(6):975–91.
2. Bransford DR, Howley ET. Oxygen cost of running in trained and untrained men and women. *Med Sci Sports Exerc*. 1977;9(1):41–4.
3. Borg G. The rating of perceived exertion scale. *Med Sci Sports Exerc*. 1982;14:377–87.
4. Cavagna GA, Saibene FP, Margaria R. Mechanical work in running. *J Appl Physiol*. 1964;19:249–56.
5. Church TS, Earnest CP, Morss M. Field testing of physiological responses associated with Nordic walking. *Res Q Exerc Sport*. 2002;73:296–300.
6. Di Prampero PE, Pendergast DR, Wilson DW, Rennie DW. Blood lactic acid concentrations in high velocity swimming. In: Eriksson B, Furberg B, editors. *Swimming Medicine IV*, Baltimore (MD): University Park Press; 1978. p. 249–61.
7. Dixon SJ, Collop AC, Batt ME. Surface effects on ground reaction forces and lower extremity kinematics in running. *Med Sci Sports Exerc*. 2000;32(11):1919–26.

8. Glasheen JW, McMahon TA. Arms are different from legs: mechanics and energetics of human hand-running. *J Appl Physiol*. 1995;78(4):1280–7.
9. Hardin EC, van den Bogert AJ, Hamill J. Kinematic adaptations during running: effects of footwear, surface, and duration. *Med Sci Sports Exerc*. 2004;36(5):838–44.
10. Kleindienst FI, Michel KJ, Schwarz J, Krabbe B. Comparison of kinematic and kinetic parameters between the locomotion patterns Nordic walking, walking and running. *Sportverl Sportschad*. 2006;20:25–30.
11. Lee IM, Paffenbarger RS Jr. Physical activity and stroke incidence: the Harvard Alumni Health Study. *Stroke*. 1998;29:2049–54.
12. Lejeune TM, Willems PA, Heglund NC. Mechanics and energetics of human locomotion on sand. *J Exp Biol*. 1998;201:2071–80.
13. Morgan DW, Bransford DR, Costill DL, Daniels JT, Howley ET, Kahenbuhl GS. Variation in the aerobic demand of running among trained and untrained subjects. *Med Sci Sports Exerc*. 1995;27(3):404–9.
14. Nigg BM, Yeadon MR. Biomechanical aspects of playing surfaces. *J Sports Sci*. 1987;5:117–45.
15. Pai YC, Wening JD, Runtz EF, Iqbal K, Pavol MJ. Role of feedforward control of movement stability in reducing slip-related balance loss and falls among older adults. *J Neurophysiol*. 2003;90:755–62.
16. Pinnington HC, Dawson B. Running economy of elite surf iron men and male runners, on soft dry beach sand and grass. *Eur J Appl Physiol*. 2001;86:62–70.
17. Porcari JP, Hendrickson TL, Walter PR, Terry L, Walsko G. The physiological responses to walking with and without Power Poles™ on treadmill exercise. *Res Q Exerc Sport*. 1997;68:161–6.
18. Rodgers CD, VanHeest JL, Schachter CL. Energy expenditure during submaximal walking with Exerstriders®. *Med Sci Sports Exerc*. 1995;4(4):607–11.
19. Saibene F, Minetti AE. Biomechanical and physiological aspects of legged locomotion in humans. *Eur J Appl Physiol*. 2002;88:297–316.
20. Schiffer T, Knicker A, Hoffmann U, Harwig B, Hollmann W, Strüder HK. Physiological responses to Nordic walking, walking and jogging. *Eur J Appl Physiol*. 2006;98:56–61.
21. Sorensen KL, Hollands MA, Patla E. The effects of human ankle muscle vibration on posture and balance during adaptive locomotion. *Exp Brain Res*. 2002;143:24–34.
22. Soule RG, Goldman RF. Terrain coefficients for energy cost prediction. *J Appl Physiol*. 1972;32:706–8.
23. Strömme SB, Ingjer F, Meen HD. Assessment of maximal aerobic power in specifically trained athletes. *J Appl Physiol*. 1997;6:833–7.
24. Willson J, Torry MR, Decker MJ, Kernozek T, Streadman JR. Effects of walking poles on lower extremity gait mechanics. *Med Sci Sports Exerc*. 2001;33(1):142–7.
25. Wright IC, Neptune RR, van den Bogert AJ, Nigg BM. Passive regulation of impact forces in heel-toe running. *Clin Biomech*. 1998;13:521–31.
26. Zamparo P, Perini R, Orizio C, Sacher M, Ferretti G. The energy cost of walking or running on sand. *Eur J Appl Physiol*. 1992;65:183–7.