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SURFACE STIFFNESS AFFECTS JOINT LOADING IN RUNNING

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The purpose of this study was to analyze adaptations in joint loading (joint moments) to running surfaces of different stiffness levels when running barefoot or shod at a speed of 3.5 m/s. Joint moments in the sagittal and frontal plane of movement were calculated using standard inverse procedures using a Vicon Nexus system and a Kistler force platform. Adaptations in joint moments were similar in direction when running on softer surfaces and when running shod compared to barefoot. Surface effects were much higher in barefoot running compared to shod running. Joint moments were increased at the hip and ankle and slightly decreased at the knee when running on harder surfaces or when running barefoot compared to shod. Joint loading adaptations corresponded with adaptations in the runner's striking behaviour. The results of this study can be used to control loading intensity in the design of training regimes for athletes or recreational runners.

KEY WORDS: barefoot running, running surface, running kinetics.

INTRODUCTION: Barefoot running has been used by track and field athletes as a training method to improve strength and proprioceptive capacities of their lower limbs and feet. Intuitively, coaches know that with the removal of the shoe's protection and guidance from their athletes feet, they increase the loading of the biological structures (muscles, tendons, ligaments) surrounding the small feet and ankle joints and induce a training stimulus. Recent research gives evidence that barefoot running leads to a more plantar – flexed footfall pattern and it has been proposed that barefoot running can reduce the risk of running injuries by decreasing the impact forces (De Wit et al., 2000; Lieberman et al., 2010). Still, a widely ignored side effect of striking in a more plantar - flexed configuration is that that the moment arms of the GRF to the lower extremity joints are altered and therefore joint loading (joint moments) might be changed (Braunstein et al., 2010). Further, almost all of the biomechanical comparisons between barefoot and shod running were performed on one, mostly very rigid running surface. Therefore, the knowledge on how joint loading is altered when running on surfaces of different stiffness levels is very limited. Furthermore, it is not known if surface stiffness levels affect joint loading to a different extent when running barefoot or shod. This knowledge could be very helpful in order to correctly predict the intensity of barefoot running training regimes, both for athletes as well as for recreational runners. Therefore, the purpose of this study was to investigate adaptations in joint moments when running shod and barefoot on surfaces of different stiffness levels.

METHODS: External joint moments at the ankle, knee and hip joints of 20 male (age: 24.3 ± 2.4 years; height: 1.81 ± 0.05m; mass: 74.4 ± 5.7 kg) and 19 female (age: 25.8 ± 3.7 years; height: 1.71 ± 0.06 m; mass: 59.8 ± 8.0 kg) subjects were calculated by means of standard inverse dynamics procedures. Subjects were running at a speed of 3.5 m/s ± 5% on four different running surfaces. The reference surface was a stiff 10 mm tartan surface that covers the entire lab and the indoor track and field facility, in which the lab is located. In the second condition, a 13 mm EVA foam was attached to the top of the base surface by double sided tape over the entire running distance of 25 m. The third condition incorporated an artificial turf surface (T-Turf S9 Revolution, TISCA Tischhauser & CO. AG, Bühler, Switzerland) that was again attached to the top of the tartan surface while the fourth condition was a combination of EVA foam and artificial turf. Surface characteristics were determined by means of a material testing machine (ElectroPuls E 10000, Instron Deutschland GmbH, Pfungstadt, Germany) using a trapezoidal testing regime. Force was build up in 0.1 s up to 1800 N, kept constant for

0.04 s and was removed in 0.1 s by a circular steel indenter (radius 0.05 m) in order to replicate a typical vertical GRF curve of an average subject running at 3.5 m/s. Material testing results are presented in table 1. GRFs were captured using a force platform (1250 Hz, 0.9 m x 0.6 m, Kistler AG, Winterthur, Switzerland) that was covered with the same surfaces as the rest of the runway, while ensuring that no contact existed between the force platform's surface and the rest of the runway. A ten camera Vicon Nexus system (250 Hz, Vicon Motion Systems, Oxford, UK) was used to track the motion of markers attached to the runner's right lower extremity and pelvis in order to measure the necessary kinematics for the inverse dynamics procedures. Running was performed barefoot and in a neutral running shoe (Brooks Glycerin, Brooks Sports Inc., Bothell WA, USA).

A two factor (shoe and surface), general linear model repeated measures ANOVA was applied to the dataset. If a significant main effect was observed, post hoc tests using Sidak correction were performed to identify detailed differences between conditions. Effect sizes (Cohen's d) for the differences between the three softer surfaces and the reference surface (Tartan) were calculated in order to estimate the relevance of any significant difference.

Table 1
Surface characteristics

		Tartan	Tartan + EVA	Tartan + Artificial Turf	Tartan + EVA + Artificial Turf
Mean Stiffness [N/mm]	mean	1628.4	185.6	321.5	134.1
	std	0.7	0.1	0.9	0.3
Stiffness 0 - 33 % deformation [N/mm]	mean	1537.5	148.9	129.1	96.0
	std	16.7	1.3	1.0	0.9
Stiffness 33 - 66 % deformation [N/mm]	mean	1794.0	152.0	220.6	132.1
	std	5.8	1.8	7.7	0.8
Stiffness 66 - 100 % deformation [N/mm]	mean	1440.0	298.1	593.4	220.6
	std	50.49	10.98	6.19	6.37
Absorbed energy [J]	mean	1.13	8.20	3.41	10.83
	std	0.00	0.07	0.01	0.07
Returned energy [J]	mean	0.74	5.98	1.57	6.93
	std	0.00	0.07	0.01	0.05
Hysteresis [%]	mean	34.5	27.0	54.0	36.0
	std	0.1	0.3	0.1	0.2

RESULTS: Systematic and significant shoe and surface effects were obtained for all three analyzed joints in the sagittal plane of movement. Running barefoot introduced adaptations in the same direction as running on harder surfaces. Ankle joint loading was increased when running barefoot or on harder surfaces, both in the sagittal and frontal plane (effect sizes between 0.33 – 0.81 between hardest and softest surface). In particular, maximum ankle joint moments were increased by 6% and in the sagittal and 12% in the frontal plane. Knee joint loading was least affected by alterations in surfaces or running footwear. Still, shoe effects on knee joint loading were on average larger than surface effects. During barefoot running, softer surfaces tended to increase knee flexion moments (difference between softest to hardest surface in maximum knee flexion moments: +5%). In shod running, a general increase in flexion moments was found (between 8 – 12%). No significant differences were found between surfaces for maximum knee adduction moments. Still, a significantly higher angular knee adduction impulse was found when wearing running shoes (+2% - 10% in the respective conditions). At the hip, surface effects dominated shoe effects. Strongest adaptations were found in the maximum initial flexion moment (17% increase, d = 0.70 between softest compared to hardest surface in barefoot running). Surface effects were on average higher in barefoot running. Consequently, significant interactions between shoe and surface effects were indicated for maximal hip extension and flexion moments, maximal knee flexion moment and angular impulse as well as maximum ankle dorsiflexion and eversion moments and angular impulses. The striking behaviour of the lower extremity was systematically altered when running barefoot compared to shod and also when running barefoot on different surfaces. In shod running striking kinematics were changed only to a minor extend on the different surfaces (fig. 2).

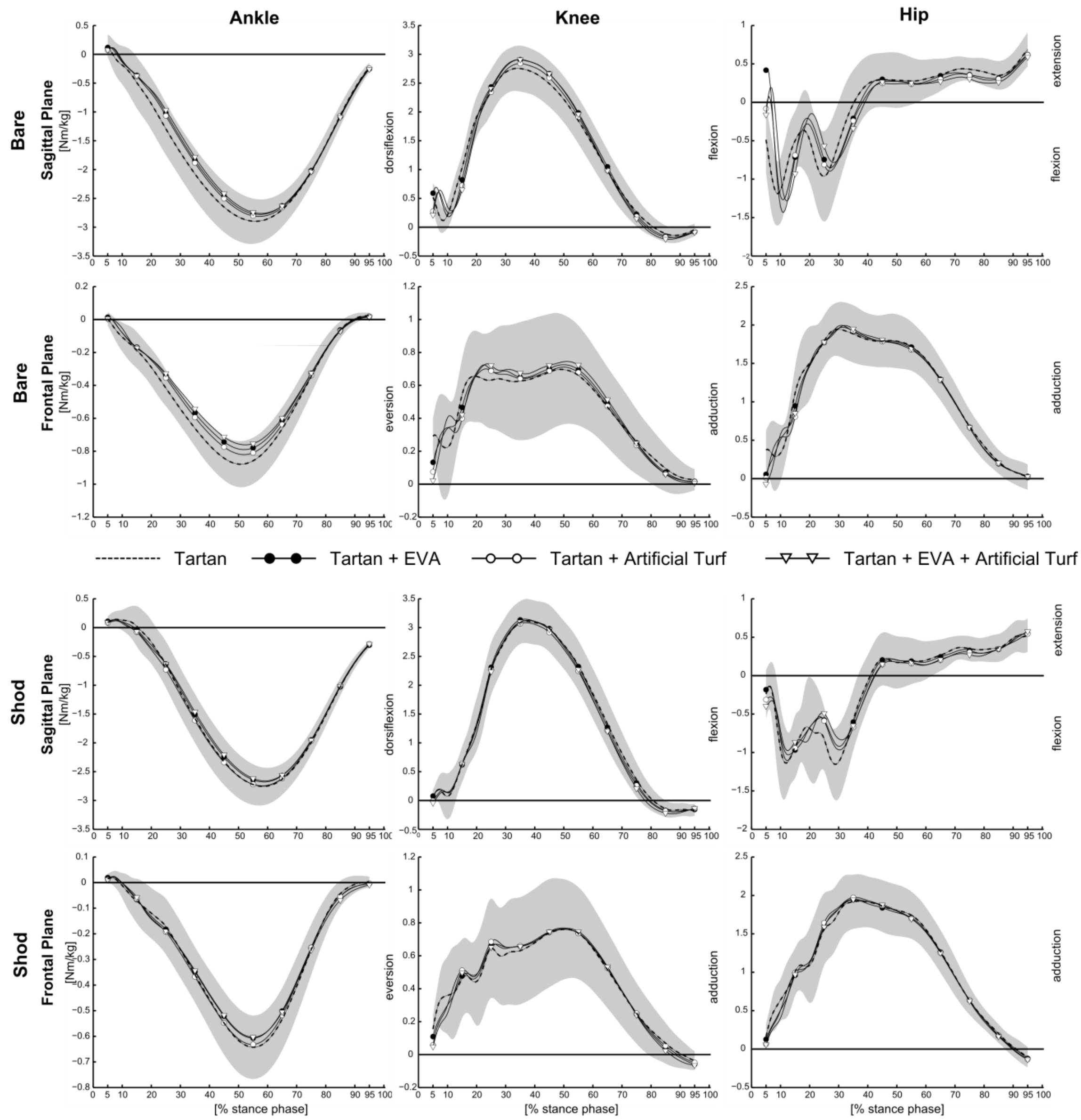

Figure 1: Lower extremity external joint moments. Shaded areas represent the mean of the Tartan condition ± one standard deviation.

DISCUSSION: The results of the present study indicate that joint loading is systematically altered as a function of surface stiffness in barefoot running. Observed increases in joint loading were on average in the size of around 10%. Considering the large number of load applications during running, these increases can be expected to induce adaptations in the capacities of lower extremity muscle tendon units, even though the single loading intensity is quite low compared to traditional strength training. Interestingly, running shod introduced loading and touchdown kinematics adaptations in the same direction as running on softer surfaces. It seems that soft materials, either in the running surface or in the midsole of a running shoe allow for more dorsiflexed heel strike behaviour. Altering the striking behaviour changes the position of the point of force application (PFA) either to the front edge of the foot (mid-, or forefoot striking) or the heel region (rearfoot striking). It has been considered that striking patterns in barefoot running are altered in order to avoid local pressure peaks and associated pain underneath the heel. (De Wit et al., 2000). A similar mechanism might explain adaptations in barefoot running found in the present study. Further, it might also explain why only minor or no adaptations occurred during shod running, since the heels are already protected by cushioning materials inside the midsole. The softest running surface was softer than the cushioning materials of the neutral running shoe, but alterations in striking configuration were more intense for shod running compared to the differences between softest and hardest surface. Therefore, it seems that the geometry of the running shoe might play a further role in striking behaviour and joint loading adaptation. Loading changes in the frontal plane of movement might be explained by a systematic shift of the PFA to the medial parts of the foot and concurring changes in frontal plane moment arms at the joints. This shift might be introduced by the fact that the longitudinal arch of the foot is more supported if the foot is penetrating the softer running surfaces, which shifts more pressure (and the PFA) underneath the medial part of the foot.

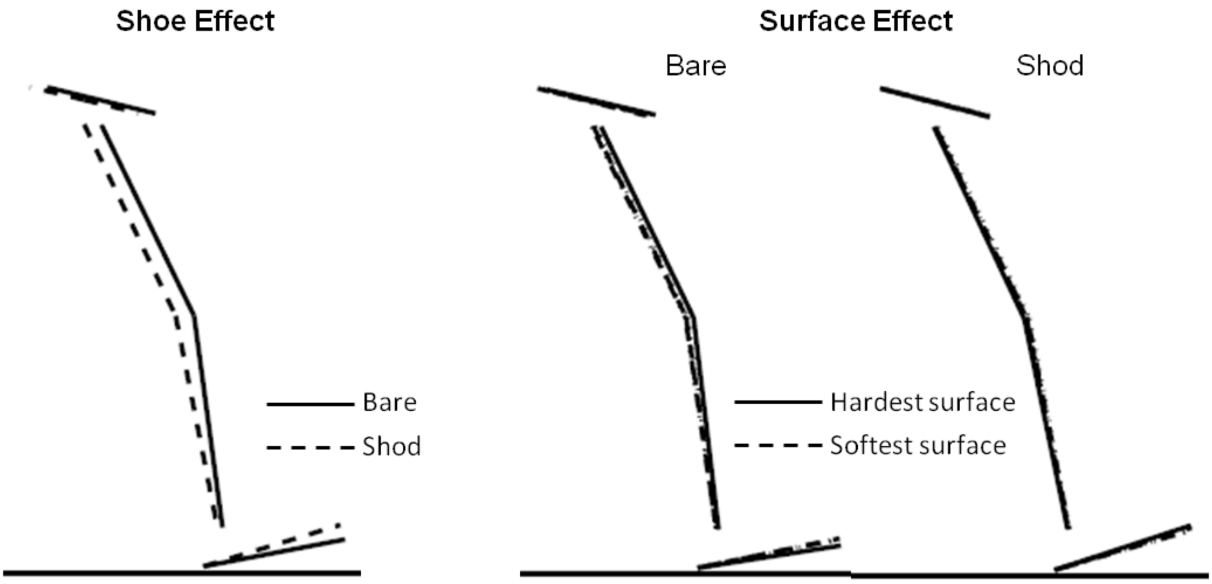

Figure 2: Kinematic adaptations of the striking behavior in the sagittal plane of movement.

CONCLUSION: The results of the present study give evidence that joint loading is influenced by the surface stiffness in barefoot running and by the use of running shoes. If training regimes are designed to increase loading intensity of muscles crossing the ankle and hip joints, it is recommended to start running barefoot on softer surfaces and subsequently increase surface rigidity in order to increase the training stimulus. The same recommendations can be given if runners want to change from running with traditional running shoes to minimal footwear or barefoot running. Still, the risk to sustain overuse injuries like achillo – tendinitis or plantar fasciitis might be increased, if no proper adaptation period to higher joint loads is provided.

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