A COMPARISON OF LOWER EXTREMITY FORCES, JOINT ANGLES, AND MUSCLE ACTIVITY DURING SHOD AND BAREFOOT RUNNING

Matthew Stockton, Rosemary Dyson,
Chichester Institute of Higher Education, England

INTRODUCTION: Amongst others Clarke (1983) investigated different sole configurations and barefoot running. Robbins and Gouw (1990) promoted consideration of the body's impact protection system and expressed concern about imparired sensations in some modern shoes. De Wit and De Clercq (1997) detailed barefoot body kinematic adaptations. Muscular activity differences between shod and barefoot running may aid understanding when considered relative to force and kinematics.

METHODS: Nine male competitive heel strike runners who ran regularly volunteered for the study and gave informed written consent. Subject characteristics (mean, S.D.) were: age 30.8 ±10.6 years; height 1.77 ±0.06m; mass 70.9 ±9.0kg. Subjects ran naturally along a polyflex track within which a Kistler 9851 force platform was mounted and covered with a 0.0013m layer of polyflex. Subjects ran, first shod and then barefoot, until eight successful natural strikes of the platform with the right foot had been recorded. All subjects wore New Balance M677 running shoes. All shoes were new to avoid the chance of sole degradation or wear characteristics influencing the data. The weight of the shoes varied from 0.33kg per shoe for UK size 7.5 to 0.38kg for UK size 10, increasing by 0.01kg with each increasing half size. The subjects were given time to become accustomed to running in the shoes or running barefoot prior to testing by running around a grass track and on the polyflex track, and subjects practised landing on the platform at the correct speed without altering their natural stride pattern. Testing began when the subjects reported feeling comfortable running, whether barefoot or shod, at the correct pace. Data was sampled at 1000Hz and stored using Provec 3.0 software (Orthodata Ltd, Germany). Subsequently ground reaction force analysis was performed during the impact phase. Measures were normalised for each subject's body weight and comparisons made for the nine subjects using paired t tests.

For both the shod and barefoot conditions cine filming at 100 Hz was performed using a Photosonics 500 16mm camera (fitted with a 25 mm lens) which was positioned 8.8m perpendicular to the force platform. Joint markers with 0.03m outer black squares and 0.015m inner yellow markers were attached with strong double sided tape to the covering or skin at the right shoulder (lateral acromial extremity), right hip (greater trochanter), right knee (lateral condyle), right lateral ankle malleolus), and right large toe position on the right shoe. All subjects wore lycra or running shorts to minimize marker movement. For the shod and barefoot condition two of the eight successful platform trials were filmed (notional the third and the sixth trial)). Internal timing lights operating at 100Hz placed a light image on the edge of the film to allow discrimination of the film speed. Vertical and horizontal calibration was performed on the centre of the platform.

Subsequently the developed cine film image markers were digitized manually on a TDS 1057 digitizing tablet operating with Bartlett two dimensional cine analysis software running on an Archimedes computer. For one foot strike every frame from five frames prior to foot contact until the first frame when the right toe left the ground was digitized. Generalised quintic spline smoothing was performed. Disposable Medicotest electromyography electrodes were applied to the right leg skin surface above the muscle belly of the vastus medialis (VM); vastus lateralis (VL); rectus femoris (RF); tibialis anterior (TA); medial gastrocnemius (MG); lateral gastrocnemius (LG). Interelectrode spacing was 0.05m and a patella reference electrode was used. Electromographic monitoring was performed during every trial using a biomedical radiotelemetry system (MIE Medical Research Ltd, England) with 4 kilo-ohm differential amplifiers. Data was sampled at 500Hz and stored using Myodat 3.0 EMG software (Orthodata Ltd. Germany) for subsequent analysis using raw and linear enveloped electromyography analysis. The electromyography and force data collection systems were synchronised to allow accurate determination of foot strike.

RESULTS: For all subjects the mean respective speeds (mean, SD) of the eight shod and barefoot running were 4.64ms^{-1} and 4.53ms^{-1}, and these were not significantly different (P>0.05). In barefoot running the mean peak vertical impact force with respect to body weight(BW) was significantly higher, and mean minimal vertical impact lower. Also, the time to peak mean vertical impact, mean peak braking force and the stance time were significantly less in barefoot running.

Table 1. Ground reaction forces occurring in shod and barefoot running

	Shod (mean, SD)	Barefoot (mean, SD)
Peak vertical impact force (BW)	*2.233 ±0.552	*2.656 ±0.764
Time to peak vertical impact (ms)	**32 ±5	**18 ±1
Minimal vertical impact force (BW)	1.842 ±0.335**	**1.488 ±0.328
Time to minimal vertical impact (ms)	12 ±5	15 ±5
Peak braking force (BW)	0.518 ±0.113	0.575 ±0.127
Time to peak braking force (ms)	**46 ±12	**28 ±12
Stance time (ms)	*210 ±17	*199 ±18

** P< 0.001; *P< 0.02.

Time to foot first flat, maximum knee flexion, heel first off were compared with paired t tests. In barefoot running the time to foot first flat and the time taken to reach maximum knee flexion (P=0.056) occured much earlier than in shod running

Table 2. Mean ±S.D. times from impact to foot first flat, maximum knee flexion and heel first off in shod and barefoot running. *P<0.05.

	Shod (ms)	Barefoot (ms)
Foot first flat	*30 ±10	*19 ±10
Maximum knee flexion	84 ±16	63 ±19
Heel first off	109 ±11	95 ±17

For seven of the subjects joint angles were determined at the hip, knee, ankle and knee-ankle-heel (KAH) angle 10ms prior to impact, at impact, sole of the foot/shoe flat, maximum knee flexion and heel off. Two subjects were excluded because the film had not reached the correct speed in either the barefoot or shod condition, and so no direct comparison could be made.

Table 3. Mean ±S.D. angles of the leg in shod and barefoot runs

	Shod (degrees)	Barefoot (degrees)
Hip		
10ms before impact	147 ±7	149 ±5
Impact	148 ±6	149 ±5
Flat foot	146 ±8	151 ±5
Maximum knee flexion	148 ±8	148 ±6
Heel off	152 ±8	156 ±7
Knee		
10ms before impact	162 ±6	161 ±5
Impact	*162 ±5	*159 +5
Flat foot	*150 ±7	*154 +8
Maximum knee flexion	132 ±6	134 ±5
Heel off	135 ±6	138 ±6
Ankle		
10ms before impact	88 ±6	90 ±5
Impact	90 ±6	90 ±5
Flat foot	105 ±5	100 ±5
Maximum knee flesxion	87 ±5	85 ±5
Heel off	***85 ±6	***80 ±5
Knee-ankle-heel		
10ms before impact	158 ±7	155 ±10
Impact	153 ±7	150 ±9
Flat foot	137 ±5	140 ±5
Maximum knee flexion	****151 ±7	****161 ±6
Heel off	**154 ±5	**162 ±4

*P=0.09; **P<0.05; ***P<0.01; ****P<0.001.

Of the twenty paired t test comparisons only three were significant, the barefoot ankle angle was significantly lower at heel off, the barefoot knee-ankle-heel angle was significantly greater at maximum knee flexion and the barefoot knee-ankle-heel angle was significantly greater at heel off.

Qualitative analysis of within subject muscle activity indicated that for the majority of subjects in barefoot running TA activity at impact was less than in shod running, and LG and/or MG activity increased before impact. Increases in VL,VM, and RF activity were observed during barefoot running.

DISCUSSION: The first maximum vertical impact force recorded was much greater when running barefoot (265%BW) than when running shod (223%BW), and yet the minimal vertical impact force was less running barefoot (148%) than when running shod (184%BW). The significantly lower barefoot minimal vertical forces found when running barefoot agrees with Clarke (1983). These results are comparable to

De Wit et al. (1996) who reported first maximum vertical forces of 242%BW barefoot and 232%BW when shod, and minimal forces of 151%BW barefoot and 193%BW shod. In this experimental study vertical impact loading rates were twice as great when running barefoot ($14.72\%BWms^{-1}$) than when shod ($6.97\%BWms^{-1}$).

Braking occured more quickly when running barefoot and stance time was shorter, although braking forces were similar when running barefoot and shod. In barefoot running the sole of the foot reaches the ground much more quickly (Table 2) and may aid braking. Significantly less barefoot plantar flexion at maximum knee flexion (from KAH angles) and heel off were found which may reflect the raised shoe heel causing increased plantar flexion. The higher barefoot dorsiflexion at maximum knee flexion (KAH angle) may also suggest that the body was more over the foot when barefoot as reported by Komi et al (1987) and the De Wit & De Clercq (1997).

For the majority of subjects in barefoot running the increase in gastrocnemius activity commencing before impact was probably related to increased ankle plantar flexion. The lower tibialis anterior activity at impact also suggested less dorsiflexion at impact when barefoot. During barefoot running the increased activity of the knee extensor muscles vastus medialis, vastus lateralis, and rectus femoris after impact would support the concept of a more upright posture (De Wit & de Clercq, 1997).

CONCLUSION: In barefoot running increased plantar flexion of the foot occurs which will act to reduce the force on the foot by increasing the area over which general force exposure occurs. In addition the speed of response to reduce the body's exposure to external force following impact in barefoot running is much faster than when shod. These changes between running barefoot and shod in kinematics and associated preconcieved muscular actions may be evident to a limited extent with different footwear. This study also raises fundamental questions about the external physical principles causing foot injury, and the relevance and value of the body's potential neuromuscular protective mechanisms (which in the first instance are likely to involve pressure perception).

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