STRIKING TECHNIQUE AND LEG STIFFNESS IN BAREFOOT RUNNING

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The purpose of the current study was to examine the differences in leg stiffness between barefoot running styles; fore-foot/mid-foot strike (FFS/MFS) and rear-foot strike (RFS). Five active male college students between the ages of 18 and 22 (1.83 ±0.01 m; 82.10 ±5.12 kg) were recruited. Each participant performed a maximum of five 10-m runs at velocity of 4-5m/s, in each condition (FFS/MFS & RFS), over two force platforms. Vertical center of mass (CoM) oscillation, peak GRF, and leg stiffness were analyzed. Results indicated there is a significant difference in leg stiffness between FFS/MFS and RFS in the barefoot condition ($p<0.01$). These results suggested that running style is an important factor that must be controlled for when examining leg stiffness in barefoot running.

KEYWORDS: fore-foot, mid-foot, rear-foot, leg stiffness.

INTRODUCTION: Barefoot running is becoming ever more popular with claims that it can reduce injury due to less vertical ground reaction force with fore-foot or mid-foot strike (Lieberman et al., 2010). Studies have found that a fore-foot strike (FFS) and mid-foot strike (MFS), typical of barefoot running, generates a smaller ground reaction force (GRF) of 1.5–2.0 times body weight when compared to a rear foot strike (RFS), typical of shod running, which generates 1.5-3.0 times body weight (Lieberman et al., 2010; Chi & Schmitt. 2005.). Lieberman et al. (2010) speculated that this difference in technique may be a determining factor in injury rate amongst runners. A vast body of research has investigated the running efficiency and mechanisms between barefoot and shod running without conclusive findings (Dalleau et al., 1998; Chi & Schmitt, 2005). Moreover, there is no literature that examined the mechanical efficiency due to different running styles; fore-foot or rear-foot strike. Based upon current research the running technique difference between the two mediums may be responsible for the differences seen in mechanical efficiency between barefoot and shod running.

Running efficiency has been determined by the mass spring effect or leg stiffness (Farley & Gonzales, 1996; Dalleau et al., 1998). Muscles are stretched storing elastic energy, and returning the elastic energy when recoiled; this energy return results in great muscular efficiency (Farley & Gonzales, 1996). Running energy cost and leg stiffness were shown to have a significant negatively correlated relationship: as stiffness increased the energy costs of running decreased (Dalleau et al., 1998). A significant correlation between leg stiffness and stride frequency has also been shown; leg stiffness is known to increase as stride frequency increases (Dalleau et al. 1998; Farley & Gonzales, 1996). Additionally, studies have shown that barefoot running had a higher stride frequency when compared to shod running at similar speeds (De Wit et al., 2000); which indicates barefoot running may be more efficient than shod running. However, there is no studies have investigated the difference of leg stiffness between two styles of running: fore-foot/mid-foot strike and rear foot strike.

Furthermore, studies found that shod can alter the leg stiffness due the compliance of shoe design (Bishop et al., 2006). Therefore, the purpose of this study was to determine if running in a RFS manner or MFS/FFS manner results in a difference in leg stiffness while running in the barefoot condition. In controlling the strike pattern (RFS versus MFS/FFS), the running medium (barefoot) and the running speed, it was possible to determine if strike pattern in running influences leg stiffness. It was hypothesized that greater leg stiffness will be observed in a MFS/FFS when compared to a RFS while speed is held constant in the barefoot condition.

METHOD: Five active male college students between the ages of 18 and 22 (1.83 ±0.01 m; 82.10 ±5.12 kg) were recruited from northern California. The subjects all met the ACSM requirements for highly active classification, had no prior barefoot running experience, and no reported injuries. All policies and procedures for the use of human subjects were followed and approved by the university Institutional Review Board.

Each subject was required to warm-up for at least five minutes by jogging and practicing striking in front of the cameras. All subjects performed a maximum of five 10 m runs at 4-5m/s, in each condition (FFS/MFS & RFS), over two force platforms (Kistler 9286; 1080 Hz). Each subject took a half minute break between each trial. Conditions were performed in random order.

Three-dimensional coordinate data were obtained with two 60-Hz digital video cameras (Cannon) in conjunction with a motion analysis system (Vicon Motus: 9.2) and synchronized by using Remote Video Synchronization Unit. A model using 17 points which composed 14 segments was used. Anthropometric parameters from Clauser, McConville, and Young (1969) were used to calculate the location of CoM. All video trials were cropped from the 10^{th} field before the first contact with the force platform to the 10^{th} field after the last contact with the force platform. The kinematic data were then low-pass filtered using a fourth-order zero-lag Butterworth filter and a cut-off frequency (4 Hz) determined with a previously established optimization approach (Jackson, 1979). Vertical force data was synchronized with kinematic data by using event synchronization unit.

Leg stiffness was represented using a spring-mass system, in which the CoM represented the mass and the leg represented the spring. Stiffness was defined as the ratio of the force in the spring, Peak GRF, to the displacement of the spring, vertical oscillation of the CoM. (Farely & Gonzalez, 1996). Peak GRF was determined by the force plates. Vertical oscillation of the CoM was determined from three dimensional coordinate data using the vertical difference from the instant of impact to the lowest point of the stance phase. Standard T-tests were applied to compare the leg stiffness between MFS/FFS and RFS trials. To control for type I errors, Holm's correction formula was utilized to calculate new adjusted critical *P*-values $= \alpha/(n - i + 1)$, where *n* is the total number of comparisons and *i* is the order of comparison (Lundbrook, 1998). Each observed *P*-value was compared to the new adjusted critical *P*-value.

RESULTS: Table 1 shows the obtained values for the vertical CoM oscillation (m), the peak GRF (bw), the stiffness (bw/m) for both RFS and FFS, and effect size (ES) between the comparisons. A significant difference was seen between RFS and FFS/MFS conditions in vertical CoM oscillation (p= 0.0065), peak GRF (p= 0.0458), and stiffness (p= 0.0037).

Table 1: Obtained values for the vertical CoM oscillation (m), the peak GRF (bw), the stiffness (bw/m) for both RFS and FFS, and effect size (ES) between the comparisons.

	Vertical CoM Oscillation (m)*	**Peak GRF (bw)***	**Stiffness (bw/m)***
RFS	0.04 ±0.02	3.05 ±0.61	88.24 ±44.77
FFS/MFS	0.05 ±0.02	2.73 ±0.15	60.22 ±27.80
ES	-0.57	0.7	0.71

Note: * represents significant difference between running styles was found.

DISCUSSION: The results of the study support the literature in terms of peak GRF trends as well as vertical CoM oscillation (Lieberman et al., 2010; Chi & Schmitt. 2005). The RFS condition was shown to have a significantly (p=0.0458) higher GRF than the FFS/MFS. It is also important to note that vertical CoM oscillation was significantly (p= 0.0065) smaller in the RFS condition when compared to the FFS/MFS condition. This difference is in support of biomechanical analyses between a RFS in walking and a FFS/MFS in running addressed by

Bramble & Lieberman (2004); in which they note that the leg remains relatively straight in a RFS technique.

The hypothesis that FFS/MFS would have a greater stiffness was not supported by the results. Results showed that RFS had a significantly ($p = 0.0037$) greater stiffness than FFS/MFS; this difference was shown to be significant at the $p=0.01$ level. When considering that stiffness is the ratio of peak GRF to the vertical CoM oscillation it is easy to see why a RFS had a greater stiffness. As peak GRF increases and vertical CoM oscillation decreases, as is well reported for a RFS, the resulting stiffness increases as well.

Farley & Gonzales (1996) as well as Dalleau et al. (1998) note that leg stiffness is a good indicator for running efficiency in which the greater leg stiffness, the better running efficiency. Therefore, the results of the current study suggest that a RFS strike while barefoot may be conducive of better running efficiency. While the results suggest the RFS is more efficient, another important factor to consider is that a FFS/MFS dissipates GRF better than RFS as shown in the results. This technique change is important to lowering GRF rates and may lower injury rates simultaneously. Bramble and Lieberman (2004) suggest that a MFS helps to dissipate GRF while running, and therefore reduce injury rates. Although this study suggests that a RFS while barefoot may be more efficient, the results also suggest a FFS/MFS may lower injury rates in running.

The most important result of this study is that running style (FFS/MFS vs RFS) significantly impacts leg stiffness. The vast majority of current research does not control for running style and therefore may be inconclusive in their results. When examining leg stiffness running style must be controlled for in order to have meaningful results as it has a significant effect on the resulting stiffness.

The limitations of current study include that all the runners had no experience of running barefoot and the runners were forced to use techniques that may have been different from their natural running style, which may have altered their gait pattern. In addition, the lower extremity joint stiffness was not calculated which may provide more information about the difference between running techniques.

CONCLUSIONS: The current study found that there is a significant difference in leg stiffness, while barefoot, between running styles (FFS/MFS vs RFS) in active males. This difference suggests that running style is an important factor to control for when examining leg stiffness in past and future research. Further research needs to be done investigating if this principle is true across different running speeds, and in situations in which mass-spring stiffness is influenced by a compliant surface such as a shoe or terrain changes. Specific joint stiffness should also be examined between techniques to determine if striking technique is a determining factor.

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