THE INFLUENCE OF PROLONGED RUNNING AND FOOTWEAR ON LOWER EXTREMITY JOINT STIFFNESS

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The purpose of this study was to compare leg, knee and ankle stiffness over the course of a prolonged treadmill run (PTR) in neutral and stability footwear. Fourteen male habitual, rearfoot runners completed two biomechanical testing sessions where they ran for 21 minutes at their preferred running speed in a neutral shoe, then changed either into the same neutral shoe or a stability shoe and ran a further 21 minutes on a force instrumented treadmill. No differences were observed in leg stiffness ($p > 0.05$). Knee stiffness increased during the first 21 minutes ($p = 0.003$), while ankle stiffness reduced at minute 21 ($p = 0.004$) and minute 44 ($p = 0.006$). No differences were observed between footwear conditions ($p > 0.05$). These results suggest that over the course of a PTR, shock attenuation strategies change, and this change may be detrimental to the knee joint.

KEYWORDS: running, injury, footwear, knee.

INTRODUCTION: For the ever-growing population of runners, 65% will experience a running related injury each year, with the majority being overuse injuries sustained to the knee and foot (Messier et al., 2018). Anatomical predisposition, previous injury, surface, training errors and biomechanical factors have been associated with injury (Messier et al., 2018). In the effort to reduce running related injuries, footwear companies have focused on cushioning and stability in athletic running shoe design. Midsole design features are targeted as they are thought to attenuate impact loading and/or limiting ankle joint excursions by modifying the foot-ground interface.

One modifiable biomechanical variable that has been shown to be associated with both running injury and performance is joint stiffness. In its simplest form, stiffness describes the relationship between the deformation of a body and a given force. True stiffness of the human body is the combination of all individual stiffness values of the tissues (i.e., muscles, tendons, ligaments, cartilage and bone) (Latash & Zatsiorsky, 1993). However, a model that accounts for all of these factors with accurate mathematical expressions is very complex and not currently feasible. Consequently, biomechanists describe simpler mass-spring models that are representations of torsion-stiffness, often referred to as “quasi-stiffness”. The stiffness of the leg spring has been used in describing the dynamics of running and hopping. While some level of leg stiffness is necessary for performance (i.e., optimal utilization of the stretch-shortening cycle), too much or too little stiffness may lead to injury. For example, a stiffer spring will transfer greater load than a more compliant spring and may induce bony type injuries, while a very compliant spring may lead to more soft tissue type injuries (Williams, McClay Davis, Scholz, Hamill, & Buchanan, 2003).

Reduced leg stiffness has been observed during exhaustive running (Dutto & Smith, 2002), and following repeat 100m sprint efforts (Morin, Jeannin, Chevallier, & Belli, 2006). As the majority of runners do not run to exhaustion regularly, it is of interest to quantify the changes that occur over the course of a typical prolonged training run since this may be more relatable to overuse running injuries. Therefore, the purpose of this study was to determine the changes in leg and knee and ankle joint stiffness which over the course of a prolonged treadmill run (PTR). It was hypothesized that leg, knee and ankle stiffness would decrease over the course of the PTR. Secondarily, we hypothesized that no differences in leg, knee and ankle stiffness would exist when runners wore neutral or stability athletic footwear.

METHODS: Fourteen male (24 ± 4.4 years, 1.78 ± 0.05 m, 71.2 ± 8.3 kg) habitual rearfoot recreational runners participated in this study. Participants completed two 44-minute prolonged running sessions at their preferred speed (group average: 3.3 ± 0.4 $m.s^{-1}$) at the University of Massachusetts Biomechanics Laboratory on two separate occasions spaced one week apart at the same time of day. During each testing session, participants completed two consecutive 21-minute running bouts, interspersed by a two-minute period to change into a second shoe. During the first 21 minutes of both sessions, runners wore a neutral shoe. Following this, runners either changed into another neutral shoe of the exact same construction but another colour (Session A), or a stability shoe of the exact same construction but with an added medial post (Session B) and ran for a further 21 minutes (Figure 1). Shoe conditions were delivered in a block randomized order and participants were blinded to the footwear condition.

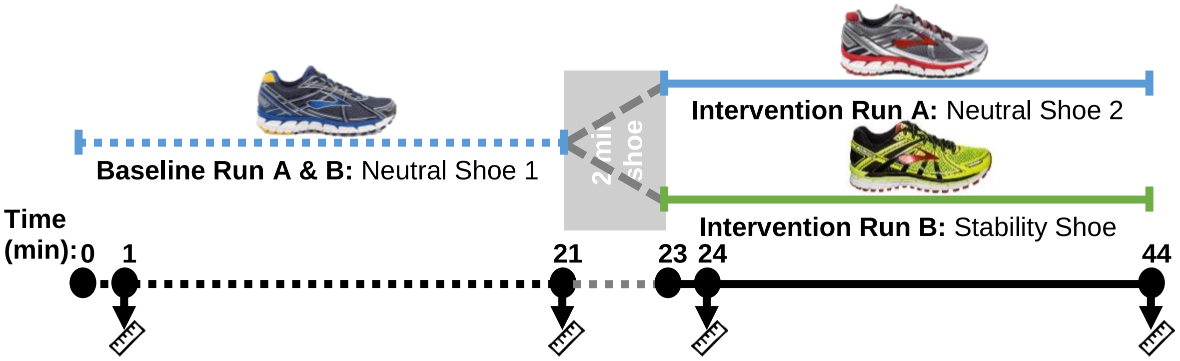

Figure 1: Experimental Design. Note: figure modified from (Weir et al., 2018).

Three dimensional (3D) kinematic and ground reaction force (GRF) data were recorded with an 8-camera motion capture system (Qualisys, Inc., Gothenburg, Sweden) and a force instrumented treadmill (Treadmetrix, Park City, UT) sampling at 200 Hz and 2000 Hz respectively. Data were collected for 15 stance phases at minutes 1, 21, 24 and 44. At each time interval, rating of perceived exertion (RPE) (Borg, 1973) and heart rate were collected using a Polar A3 HR monitor (Polar Electro Inc., Woodbury, NY). Heart rate was expressed as a percentage of each individual's estimated maximum heart rate (HR_{max}) (i.e. 220-age).
3D marker trajectories and GRFs were filtered with a zero-lag fourth-order low pass Butterworth filter at 8 Hz for the calculation of joint angles and moments. Vertical ground reaction forces were filtered separately at 25 Hz for peak vertical GRF measures. Sagittal plane knee and ankle joint moments were calculated in Visual 3D (C-motion, Inc., Rockville, MD). Leg stiffness (k_{leg}) was calculated as the ratio of the peak vertical GRF ($vGRF_{max}$) to the change in the vertical leg length (ΔL) at the instant when the centre of mass reaches its lowest point (i.e., $k_{leg} = vGRF_{max}/\Delta L$) (McMahon & Cheng, 1990). The change in vertical leg length was calculated from the change in the vertical displacement of the centre of mass (Δy), the standing leg length (L_0: the distance from the greater trochanter to the ground) and half the angle swept by the leg during stance (θ) (i.e., $\Delta L = \Delta y + L_0(1 - \cos\theta)$). Knee and ankle joint stiffness (k_{joint}) were calculated as the ratio of the change in joint moment (ΔM) to the change in the joint angle (Δθ) during stance (i.e., $k_{joint} = \Delta M / \Delta\theta$).
Due to the effect of rest in the two-minute shoe-change period, baseline and intervention phases of the PTR were analysed separately. Differences in $\%HR_{max}$, RPE and leg, knee and ankle joint stiffness were assessed with two-way within factors (session*time) repeated measures ANOVAs (α=0.05). Partial eta squared effect sizes were calculated and defined as small (η^2=0.01), medium (η^2=0.06) or large (η^2=0.14) effects (Cohen, 1988).

RESULTS: $\%HR_{max}$ and RPEs increased during the baseline ($\%HR_{max}$: ↑Δ7%, RPE: ↑Δ10%) and intervention ($\%HR_{max}$: ↑Δ5%, RPE: ↑Δ8%) phases of the PTR ($p < 0.001$, $\eta^2 > 0.6$). RPE at the end of each running phase reflected "somewhat hard" on the BORG scale. No main effect for session were observed for $\%HR_{max}$ and RPE ($p > 0.05$).

There were no differences in k_{leg} between footwear conditions or over the course of the PTR ($p > 0.05$) (Figure 2A). A significant main effect for time was observed for an increase in knee joint stiffness during the baseline phase ($p = 0.024$, $\eta^2 = 0.336$), which was maintained during the intervention phase of the PTR (Figure 2B). Significant main effects for time were observed for a decrease in ankle joint stiffness during both the baseline ($p = 0.005$, $\eta^2 = 0.460$) and intervention ($p = 0.002$, $\eta^2 = 0.540$) phases of the PTR (Figure 2C).

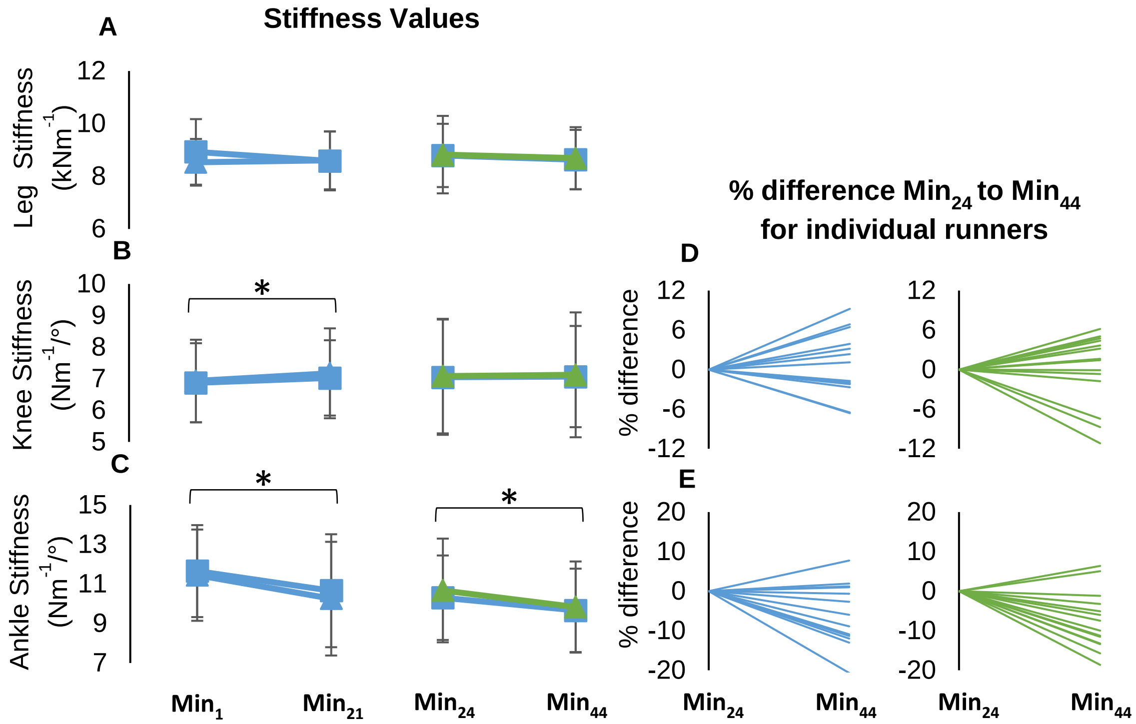

Figure 2: Leg, knee and ankle stiffness (A-C) throughout the PTR and individual % difference in knee and ankle stiffness from the start-end of the intervention run (D-E) in the neutral shoe (blue) and stability shoe (green) for sessions A (squares) and B (triangles). *Indicates main effect for time (p < 0.05).

Differences in knee joint stiffness were attributed to an increase in the knee extensor moment (i.e., ΔM) during the baseline phase of the PTR ($p = 0.003$, $\eta^2 = 0.547$), while no changes in knee flexion were observed ($p > 0.05$). Reduced ankle stiffness was a result of the ankle becoming more compliant throughout the baseline ($p = 0.004$, $\eta^2 = 0.516$) and intervention phases ($p = 0.006$, $\eta^2 = 0.483$) of the PTR (Table 1).

Table 1: Mean (SD) ankle and knee change in moment (ΔM) and range of motion (Δθ) during the baseline and intervention phases of the PTR for session A and session B.

	Session A				Session B			
	Baseline run: Neutral shoe		Intervention run: Neutral shoe		Baseline run: Neutral shoe		Intervention run: Stability shoe	
	Min_1	Min_{21}	Min_{24}	Min_{44}	Min_1	Min_{21}	Min_{24}	Min_{44}
ΔM_{Ankle} (Nm)	207.8 (34.6)	207.0 (34.8)	205.5 (27.6)	201.1 (27.2)	203.9 (31.1)	205.4 (32.8)	207.0 (29.3)	204.6 (32.3)
ΔM_{Knee} (Nm)	251.8 (44.8)	260.8 (45.5)*	258.5 (50.3)	258.7 (47.6)*	252.6 (48.2)	259.7 (49.7)	259.6 (51.8)	258.9 (51.5)
$\Delta\theta_{Ankle}$ (°)	17.9 (3.9)	20.1 (5.1)*	19.0 (3.5)	19.8 (3.7)*	17.6 (3.5)	20.3 (4.7)*	18.4 (3.5)	19.6 (3.6)*
$\Delta\theta_{Knee}$ (°)	36.5 (3.5)	37.0 (3.9)	36.3 (4.4)	36.2 (3.9)	36.2 (3.9)	35.7 (3.8)	35.9 (3.8)	35.5 (3.9)

*Main effect for time (p < 0.05)

DISCUSSION: The primary hypothesis of this study was primarily rejected. There was no change in overall leg stiffness, however, we observed increases in knee joint stiffness and

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decreases in ankle joint stiffness over the course of the 44-minute PTR. Our second hypothesis was supported where as a group, no differences were observed in stiffness values when runners wore neutral and stability running shoes.

Increased knee stiffness has been observed in injured vs uninjured runners in both prospective (Messier et al., 2018; Williams et al., 2003) and retrospective (Hamill, Moses, & Seay, 2009) studies. As knee joint stiffness increases, shock attenuation would decrease and consequently, ground contact forces would be transferred up the kinematic chain to the low back and possibly all the way to the head. In order to attenuate the foot-ground shock at foot strike, one strategy would be to increase the knee flexion angle thus reducing knee joint stiffness. However, increasing knee flexion angle increases energy expenditure (Valiant, 1990). In the current study, knee angle remained constant over the course of the run so this strategy was not employed. Consequently, increased knee joint stiffness occurring over the course of a run may be a factor for running-related injuries due to higher loads being applied to the knee joint while it maintains a similar posture. Additionally, the extent of the increase of knee stiffness from individual to individual may provide insight into runners who are more at risk of injuries than others.

It appears that, in order to maintain the total system stiffness over the course of a PTR, increased compliance of the ankle joint and consequent reduction in stiffness occurred. This strategy has been observed in studies comparing joint stiffness in runners with differing foot strike techniques (Hamill, Gruber, & Derrick, 2014). Finally, there was no influence of stability vs neutral footwear on stiffness values when considering the average across all individuals. However, upon inspection of individual data (i.e., Figure 2D and 2E), some runners had similar responses to footwear while others responded better (i.e., did not increase knee joint stiffness) to neutral shoes and others better to the stability shoes.

CONCLUSION: Over the course of a PTR, leg stiffness is maintained while knee stiffness increases and ankle stiffness decreases. These changes are modulated by increased ankle joint range of motion and knee joint moments, and may have implications for the high incidence of knee injuries in runners. Footwear effects on joint stiffness are individual to the runner.

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