HIGH LEVELS OF ENDURANCE TRAINING MITIGATE AGE-RELATED CHANGES IN RUNNING BIOMECHANICS – A LONGITUDINAL STUDY

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Very few studies to date examined lower body and joint stiffness in ageing endurance runners, the majority cross-sectionally. The present study longitudinally examined age-related changes in leg and joint stiffness regulation in consistently trained master endurance runners, as well as the contribution of individual joints in resisting collapse and generating propulsion. Highly trained master endurance runners (N=10) were studied over a period of seven years whilst maintaining their training regime. Data was collected at mean age 53.54 ± 2.56 and 60.49 ± 2.56 following an identical overground running protocol, using a Kistler force plate and a 12-camera Vicon motion capture system. Following seven years of ageing, leg stiffness was unchanged. The athletes maintained similar magnitudes of joint stiffness and moment at the ankle and the hip whilst knee joint stiffness at amortisation increased by 0.60^{o-1} ($p<0.01$, $d=2.67$) and knee extensor moment by 158% ($p<0.01$, $d=3.07$). The support moment at amortisation increased by 31% and combined joint stiffness by 10%, with a double and triple increase in the relative contribution of the knee joint. The ageing master runners showed a biomechanical strategy characteristic for high levels of training rather than ageing gait - higher forces, increased step length and decreased ground contact time. It appears that consistently high training can help maintain stiffness regulation capacity with ageing and attenuate the distal-to-proximal shift in running biomechanics.

KEYWORDS: Master Athletes, Ageing, Running, Stiffness, Longitudinal Study

INTRODUCTION: Examining master athletes can offer a blueprint of successful human biological ageing decoupled from sedentarism and deconditioning (Lazarus and Harridge, 2017). There are very few longitudinal studies on endurance runners who despite their age maintained a high training volume and intensity (Lepers et al., 2021). The existent cross-sectional ageing biomechanics studies often include older participants with lower weekly mileage and training speeds compared to the young. Biomechanically, the trademark of ageing gait is a general loss of propulsive force, owing to the decreased moment and power output of ankle plantar flexors (DeVita et al., 2016). Older runners generate lower ground reaction forces (GRF) than the young (DeVita et al., 2016), adapting their running strategy to match the neuromuscular limitations (Kamanidis and Arampatzis, 2005) and impaired impact attenuation (Diss et al., 2015). Compared to the young, they have shorter step length and increased step frequency running for the same speeds. In addition, running studies (DeVita et al., 2016) found that due to mechanical reductions at the ankle, older adults seem to redistribute power generation proximally - to the hip joint. The hip extensors have shorter tendons than the plantarflexors, with less capacity to store and return elastic energy, so this shift might negatively affect running performance (Paquette et al., 2021).

Interestingly, the distal-to-proximal redistribution pattern seems to be more pronounced in less trained individuals (Willy and Paquette, 2019). Paquette et al. (2021) matched trained runners in their late 50s with young runners based on either their training volume or training intensity and found similar ankle kinetics in the groups matched by intensity, regardless of age. The distal-to-proximal shift was still present but to a much smaller degree in trained older participants than in the untrained older control group distal to when young and older athletes were matched sing training volume. It therefore appears that the quality and rate of changes in running biomechanics in older athletes is to a good extent training dependent.

Running is a weight-bearing activity with a bouncing mechanism. Leg stiffness describes a relationship between GRF and leg-spring compression. Additionally, each lower limb joint can be pictured as a torsional spring with joint stiffness representing a relationship of the joint moment and the corresponding angular displacement. However, it is not clear how the bouncing mechanism in running changes with ageing, as the studies are inconclusive (Powell and Williams, 2018). The present study aims to longitudinally examine running biomechanics in consistently highly trained master endurance runners over seven years of ageing. It was hypothesised that the master runners would retain similar leg and joint stiffness, maintain a reliance on the ankle joint in support moment while transitioning from absorption to propulsion.

METHODS: Ten male endurance runners 53.54 ± 2.56 years old (M50) volunteered to participate in the study and returned for the 2nd data collection seven years later, mean age 60.49 ± 2.56 years (M57), mass remained unchanged. There was strict criterion for inclusion regarding their training regime and ability such as the continuarion of two interval sessions/week. Upon obtaining a written informed consent, the data collection protocol was approved by the Ethics Board of the University of Roehampton. Three-dimensional (3D) coordinate data was obtained using the Vicon 12-camera motion capture system (Vicon™, Oxford; 120 Hz) synchronised with a force plate (Kistler™, Switzerland, 9281C; 1080 Hz). Each participant performed multiple running trials at a horizontal velocity of 3.83 ± 0.40 $m \cdot s^{-1}$ and made right foot contact with the force plate.
Six trials/participant were analysed from which means (standard deviation) were determined for each measure. 3D coordinate marker data was reconstructed using non-linear transformation and filtered with Woltring's cross-validated quintic spline (mean square error noise tolerance set at 15 mm^2). Lower body joint centres and sagittal plane angles and moments were determined using vector-defined segments and inverse dynamics analysis.
Stance was defined as a period between initial foot contact with the force plate (vertical GRF (vGRF) > 8 N) and toe-off (vGRF < 8 N) and subdivided into absorption and propulsion phase, distinguished by amortisation. Amortisation was defined as a time point when the resultant vertical and anteroposterior displacement of the body's centre of mass was minimal (Diss et al., 2015). Horizontal GRF (hGRF), vGRF, joint kinetics and kinematics were examined over time-normalised stance. Leg stiffness was calculated using the simple spring-mass model (McMahon and Cheng, 1990) as a change of the resultant vGRF and hGRF in the absorption phase divided by the corresponding lower-body compression (normalised to leg length). Joint stiffness at amortisation was computed for hip, knee and ankle joint as a change of joint moment in absorption phase, divided by the corresponding change in joint (RoM).
The discrete measures were statistically analysed in SPSS (IBM SPSS Statistics, Version 26.0.) using either a one-way ANOVA (parametric) or Wilcoxon Signed-Rank test (non-parametric). In addition to statistical significance (alpha-level 0.05), differences were quantified through Cohen's d effect size and percentage of change for each variable.

RESULTS: Following seven years of ageing, leg stiffness at amortisation remained unchanged. Maintaining the same running velocity, step length significantly increased with a decrease in frequency and a greater peak propulsive hGRF. Although stance duration non-significantly decreased, amortisation occurred earlier as a percentage of the stance.
While knee joint stiffness at amortisation increased by 0.60^{o-1} in magnitude (% change = 241%, p<0.01*, d=2.67*), the change in ankle and hip stiffness remained insignificant (p=0.29, d=0.52; p=0.24, d=0.02). Total combined joint stiffness at amortisation increased by 10% with the relative contribution of knee stiffness growing from 7.82% to 24.18%. The contribution of ankle stiffness in total joint stiffness at amortisation decreased from 44.2% to 31.7% while the contribution of hip stiffness dropped from 48% to 44.2%.

Table 1. Mean (±SD) are presented for each discrete measure. Red indicating a significant difference and * a large effect sizes (Cohen's d ≥ 0.80).

	M50	M57	p	Diff.	d
Running velocity (m/s)	3.81±0.39	3.83±0.40	0.57	+1%	0.05
Step Length (m) *	1.35±0.21	1.48±0.17	0.02	+10%	0.72
Step Frequency (Hz) *	2.81±0.27	2.61±0.28	0.01	-7%	0.77
Stance duration (s) *	0.24±0.03	0.22±0.03	0.01	-8%	0.70
Peak propulsive hGRF (BW) *	0.31±0.05	0.37±0.11	<0.01	+19%	0.74
Peak braking hGRF (BW)	-0.44±0.12	-0.58±0.19	0.11	32%	0.93*
vGRF at impact peak (BW) *	1.92±0.38	2.33±0.40	0.01	+21%	1.11**
vGRF at amortisation (BW)	2.54±0.25	2.76±0.67	0.29	+9%	0.46
Time of amortisation (% stance) *	45.86±2.95	40.53±2.53	<0.01	-12%	2.04**
vGRF max (BW)	2.61±0.25	2.79±0.67	0.51	+7%	0.38
Time of vGRF max (% stance)	41.56±3.94	39.95±4.48	0.17	-4%	0.40
Hip RoM (deg) *	10.01±3.42	7.27±2.78	0.04	-27%	0.93*
Knee RoM (deg)	30.00±5.61	27.34±5.64	0.17	-9%	0.50
Ankle RoM (deg)	14.64±4.80	15.96±3.60	0.47	+9%	0.33
Lower body spring compression	0.06±0.02	0.06±0.03	0.96	0%	0.00
Leg stiffness at amortisation	49.71±15.59	49.70±20.2	1.00	0%	0.00

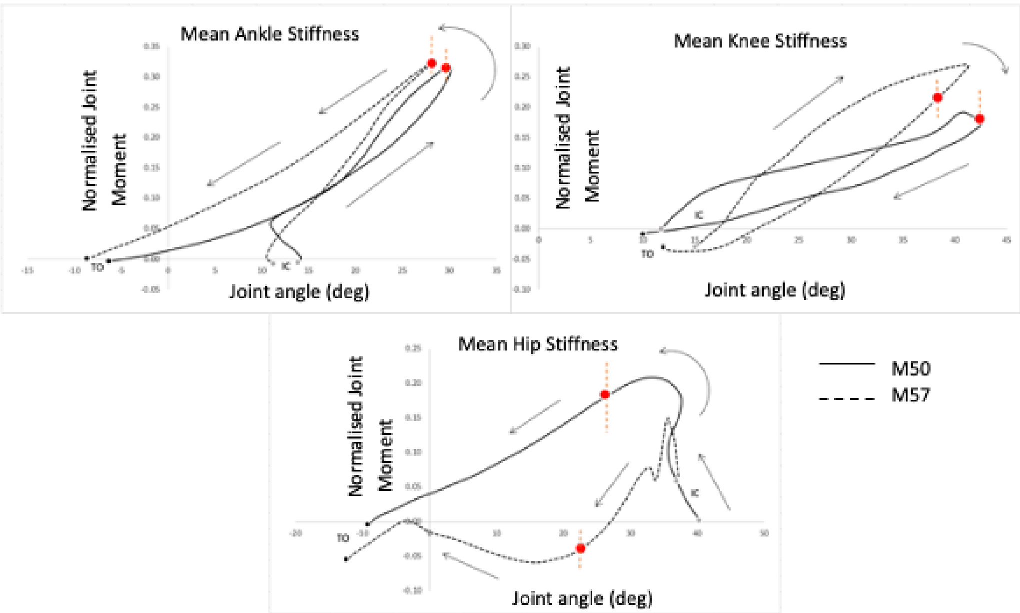

Figure 1. Joint moment-angle scatterplots for ankle, knee and hip – joint stiffness is represented as a gradient of the curve during stance. Grey dots – initial contact, black dots – toe off, red dots amortisation.

DISCUSSION: The purpose of the present study was to examine longitudinal changes in running biomechanics with ageing in consistently highly trained master endurance runners. The focus was on leg and joint stiffness and individual joint contributions to combined joint stiffness and support moments during the transition from absorption to propulsion. Leg stiffness at amortisation was unchanged, however joint stiffness magnitudes remained similar at the ankle and the hip but greatly increased at the knee which was attributed to an increased knee moment. The capacity of ageing runners to further increase stiffness at the knee joint despite ageing is a novel finding. Cross-sectional studies examining joint stiffness in less trained older participants generally found lower knee joint stiffness (Powell and Williams, 2018). According to Powell and Williams (2018) older runners rely on skeletal structures rather than muscles for support, showing a higher vertical component of leg stiffness than the young, but lower joint stiffness at the knee and the ankle. This would correspond to the commonly observed safety-focussed motor task execution strategy in ageing adults. However, master runners in the

present study appeared to optimise their strategy for performance instead, which can be attributed more to their training level than their age. Following seven years of ageing, their lower limb neuromuscular capacity appears to have remained high, allowing them to increase the step length, reduce step frequency, generate higher vGRF and further decrease the ground contact time to effectively stiffen the leg. The propulsion demands did effectively move proximally – from the ankle to the knee, but not yet to the hip joint, as in the typical distal-to-proximal pattern in older athletes. These findings are consistent with the recent studies by Paquette et al. (2021) where maintaining the training volume and intensity could help attenuate the distal to proximal power redistribution commonly observed in ageing gait.
The age of 60, which was the mean age at the second data collection, is often seen as a "point of no return" followed by an accelerated neuromuscular decline (Lepers et al, 2021). Therefore, it is possible that compensation patterns are just emerging at this point. Examining the ankle joint kinematics (Table 1) there was a visible but statistically insignificant increase in ankle RoM during absorption – which decreased in duration as the stance duration decreased, implying an increase in ankle angular velocity. This might be a beginning of a pattern of increasing ankle angular velocity to preserve ankle power output at amortisation, as joint power is a product of moment and angular velocity. However, maintaining a capacity for increasing ankle angular velocity can help maintain consistent ankle power output and propulsive force generation and counteract the age-related decline in running speeds (Paquette et al., 2018). A limitation to the study was an absence of a control group to determine the repeatability of the measures examined and meaning to any change in their magnitude observed.

CONCLUSION: After seven years of ageing the master endurance runners increased their knee joint stiffness through a large increase in the knee extensor moment. It appears that with consistently high training volume and intensity it is possible to maintain the stiffness regulation capacity with ageing and attenuate the age-related changes in running biomechanics.

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