Abstract

The aim of this study was to examine the age-based, lower limb kinetics of running performances of endurance athletes. Six running trials were performed by 24 male athletes, who were distinguished by three age groupings (S35: 26 - 32 years, M50: 50 - 54 years, M60 +: 60 - 68 years). Lower limb coordinate and ground reaction force data were collected using a nine camera infra-red system synchronised with a force plate. A slower anteroposterior (M ± SD S35 = 4.13 ± 0.54 m/s: M60 + = 3.34 ± 0.40 m/s, $p < 0.05$) running velocity was associated with significant ($p < 0.05$) decreases in step length and discrete vertical ground contact force between M60 + and S35 athletes. The M60 + athletes simultaneously generated a 32% and 42% reduced ($p < 0.05$) ankle joint moment when compared to the M50 and S35 athletes and 72% ($p < 0.05$) reduction in knee joint stiffness when compared to S35 athletes. Age-based declines in running performance were associated with reduced stance phase force tolerance and generation that may be accounted for due to an inhibited force-velocity muscular function of the lower limb. Joint-specific coaching strategies customised to athlete age are warranted to maintain/enhance athletes' dynamic performance.

Word Count: 200 words

Key words: *Ageing, Running Gait, Lower Limb Kinetics*

Introduction

Biomechanical research into endurance running has been extensive and mostly concerned with examining the mechanisms of, and potential for overuse injury rather than performance (Buist et al., 2010; Lee, Reid, Elliott, & Lloyd, 2009; Novacheck, 1998). The popularity of endurance running as a recreational activity continues to be high and almost every city in Western society has its own marathon and recreational running events (Bus, 2003). While competitive and recreational athletes from diverse age groups and socio-economic backgrounds subscribe to the respective events, the master athlete (male or female athlete aged over 35 years) has explicitly become more established in sports performance (Athletics Weekly, 2010) over the last two decades. Clear health benefits are evident for older adults who maintain participation in exercise and physical activity (Grabiner & Enoka, 1995; Tarpenning, Hamilton-Wessler, Wiswell, & Hawkins, 2004) but limited understanding of the performance implications of ageing for competitive endurance athletes exists. In addition to the systemic health benefits of regular exercise, athletic training in older adults may successfully preserve muscle function for dynamic performance. Tarpenning et al. (2004) highlighted that extensive prolonged exercise can be beneficial in preserving fibre morphology and peak joint moment values. More recently, Power et al. (2012) suggested that life-long competitive runners had greater numbers of motor units in the tibialis anterior compared to recreationally active individuals. Exposure to regular athletic training may minimise the loss of the number of motor units associated with ageing, and contribute to a maintained or marginally adapted endurance running performance in competitive master athletes**.** Disuse of the musculo-skeletal system has typically been associated with the natural sedentary lifestyle of older, inactive adults (Arampatzis, Degens, Baltzopoulos, & Rittweger, 2011) and may explain potential changes in the movement responses to everyday living tasks across the lifespan. Distinguishing the isolated biomechanical effects of disuse and ageing on athletic performance has however been problematic. A tendency to recruit untrained or sedentary older adult population has limited examination of the explicit effects of life-long athletic training (e.g. Wang, 2008) while other studies have investigated injury reduction indicators (e.g. Buist, 2010; Fukuchi & Duarte, 2008) rather than performance development implications for the ageing population. Extended insights into age-based biomechanical responses of endurance athletes are warranted to assist the development of customised training and conditioning programmes for the increasing number of older adults who maintain a physically active or competitive training regime. Endurance running performance, in terms of running velocity, is underpinned by the interaction of the step length and step frequency attained over a given distance. The maintenance of a constant anteroposterior running velocity (3.1 m/s) in older adults (age 67-73 years) has reportedly been achieved using a shorter step length (0.06 m; $p < 0.001$) but a substantially higher step frequency (0.21 Hz; $p < 0.05$) when compared to younger athletes (age 26-36 years) (Fukuchi & Duarte, 2008). Further examinations of the lower limb movement pattern adaptations have extended insights into the modified step responses made by older athletes (Bus, 2003; Derrick & Caldwell, 1998; Fukuchi & Duarte, 2008). For example, older endurance male athletes running at a self-selected velocity have been reported to elicit a greater knee flexion at the onset of the step cycle (touch-down) when compared to younger athletes (Cavagna, Legramandi, & Peyré-Tartaruga, 2008). When achieving comparable running velocities, older athletes (age over 67 years) have also been reported to use a greater degree of knee flexion at touch-down (10^{o}) than their younger counterparts (5^{o}; age 31 years) (Fukuchi & Duarte, 2008).

Attempts to examine the underlying kinetic adaptations made by older athletes have typically been limited to external force measurements in running gait investigations (Fukuchi & Duarte, 2008; Ferris, Liang, & Farley, 1999) therefore determining the joint specific contributions is merited to gain insight to their response to ageing. Previous research into the mechanics of sprint running has suggested the importance of ground contact forces rather than limb kinematics in the development of superior running velocities (Weyand, Sternlight, Bellizzi, & Wright, 2000). A reduced ability to generate active ground contact forces during the stance phase of running was reported in an investigation comparing older and younger athletes achieving similar running speeds (Cavagna et al., 2008). However, previous studies (Ferris et al., 1999; Gittoes, & Wilson, 2010) have suggested contradictory responses in the passive ground contact force generated by older and younger athletes in the pre-amortisation phase where amortisation is defined as the instance when the lower body flexion ceases prior to extension. The importance of the timing of amortisation has been recognised (Cormie et al., 2010) with reference to the release of stored elastic energy following and eccentric movement.

The influence of ageing on the ground contact forces and underlying lower limb kinetics produced in endurance running performances remains ambiguous or under-represented within the respective literature (Bus, 2003; Wang, 2008). Investigation of the lower limb kinetics including joint stiffness analyses may help to elucidate the mechanisms of adaptation in the human body (Wang, 2008). An increase in running performance has been associated with an increase in vertical and joint stiffness to aid the resistance to collapse in the eccentric phase but also to increase the rate of force production in the concentric phase (Brughelli & Cronin, 2008). Knee joint stiffness has been reported to increase from 17 to 24 N·m/^{o} when running velocity increased from 70% to 100% of the participant’s maximal velocity where the ankle joint stiffness remained unchanged

(Kuitunen, Komi, & Kyröläinen, 2002). Extended knowledge of the lower limb kinetic determinants underpinning a typical age-based decline in endurance performance may be valuable in providing insight into the neuromuscular effects attributed to the ageing process in competitive older adults. Athlete-centered training and conditioning programmes may evolve to assist the increasing numbers of master athletes involved in competitive sport. The aim of this study was to identify the influence of age on running kinetics in male athletes. Lower limb kinetic responses and the associated running performances were quantitatively compared between older master athletes and a younger senior athlete group. It was hypothesised that performance would decline with age as a function of the lower limb kinetics that underpin the running step cycle.

Methods

Twenty four male endurance-trained athletes volunteered to participate in the study. The athletes were recruited at the regional cross country championship and finished in the top twenty positions in their athletics age group. The criterion for inclusion in the study required the athletes to: be injury free, participate in a minimum of five running-based training sessions per week, two of which were at an intensity that exceeded the lactate threshold, run a total weekly distance exceeding 80 km, have a personal best time for 10 km of less than 40 minutes. All athletes provided written informed consent, and ethical approval for the data collection protocol was gained from the University of Roehampton Ethics Board. Prior to the data collections, the athletes were categorised according to three age groups: senior athletes < 35 years (S35, N = eight athletes), master athletes aged 50 to 54 years (M50, N = ten athletes), master athletes > 60 years (M60 +, N = six athletes). The small group sample sizes were a result of the strict inclusion criterion required of the athletes. The S35, M50 and M60 + group means ± SD age = 29.1 ± 2.1, 51.9 ± 1.5, 64.5 ± 3.0 years, height = 1.81 ± 0.10, 1.78 ± 0.06, 1.74 ± 0.04 m and mass = 67.4 ± 7.1, 71.1 ± 7.9, 74.7 ± 8.5 kg, respectively.

Anthropometric measures were obtained from each athlete at the onset of the data collection. Reflective, passive skin markers (N = 36 markers) were placed at pre-defined anatomical landmarks in accordance with the Vicon (Vicon ^{TM}, Oxford, UK, PluginGait) and Davis et al. (1991) bilateral upper and lower body models, respectively. Sub-maximal running trials were then performed at a self-selected velocity that corresponded to the athlete’s current 10 km race pace which aimed to standardise the performance between the athletes irrespective of age and to minimise any detrimental effects to an athlete’s natural running gait which would have occurred if the velocity was controlled (Queen, Gross, & Liu, 2006).

The athletes were given a familiarisation period to establish the equivalent running velocity and to minimise the potential for targeting of the uncovered force plate, which was flush to the floor and situated 13 m along the 20 m runway. Each athlete performed multiple (typically 20) running trials (wearing their habitual running shoes) where six trials were subsequently selected for further analysis and adhered to a running velocity range of less than 0.2 m/s for the respective athlete. Three-dimensional coordinate (sample rate: 120 Hz) data of the passive markers and ground contact force (sample rate: 1080 Hz) data were collected for each running trial using a nine camera Vicon infra red system (Vicon ^{TM}, Oxford, UK) synchronised with a Kistler force plate (Kistler^{TM}, Switzerland, 9281C). The cameras were situated to enable the athlete’s marker set to be visible for a data capture volume of 2.2 m (medio-lateral, x), 5.0 m (anteroposterior, y) and 2.2 m (vertical, z). The three-dimensional coordinate data of each marker were reconstructed using a non-linear transformation (Dapena, Harman, & Miller, 1982). The respective time histories were later smoothed using Woltring's cross-validated quintic spline with the mean square error noise tolerance level set to 15 mm^2 from which the joint centres of the whole body were determined to produce a 14 segmental model. The centre of mass of each athlete was calculated from the x, y and z coordinate data and the body segmental inertial parameter as defined by Dempster (1955). Sagittal plane lower body flexion/extension angles and moments were determined using vector defined segments and standard inverse dynamic analysis (Winter, 1983), respectively.

Running performance was defined for each trial as the average velocity of the centre of mass over one gait cycle where one step included touch-down with the force plate. The stance limb was determined by the athlete's lead leg at the initiation of a run. A single step length was defined by the horizontal displacement of the ankle joint marker between the contralateral foot touch-down events. The step frequency was determined by the division of the average anteroposterior velocity of the centre of mass by the respective step length.

Stance phase kinetics of each running trial were analysed and defined between the instants of initial (touch-down) and final contact (toe-off) with the force plate. The instant at which the vertical ground contact force first exceeded a threshold of 8 N defined touch-down while toe-off was established when the vertical ground contact force subsequently first fell below the 8 N threshold. The stance phase was divided into two sub-phases: negative and positive, which were distinguished by the time of amortisation. Amortisation was established at the time when the resultant anteroposterior and vertical displacement of the whole body centre of mass was minimal during the stance phase.

The impact peak vertical force and the maximal active vertical force were determined from the vertical ground contact force data as the first and second force peaks, respectively in the time profiles. The time to maximal active vertical force and vertical force at amortisation were determined as a percentage of the total time of the stance phase.

The maximum negative and positive anteroposterior ground contact forces were determined during the stance phase. The discrete whole body ground contact force measures were normalised to the body weight (BW) of each respective athlete. The sagittal plane lower body joint moments for the stance limb were determined for the ankle, knee and hip at amortisation.

The lower body compression was defined as the deviation of the resultant anteroposterior and vertical displacement of whole body centre of mass in the negative phase between touch down and amortisation, which was normalised to leg length. The change in lower body stiffness was also determined for the stance limb from touch-down to amortisation using a simple spring mass model (McMahon & Cheng, 1990) wherein the resultant contact force was divided by the change in displacement of the centre of mass. To establish the ankle, knee and hip joint stiffness the procedure described by Kuitunen et al. (2002) was used where the change in joint moment was divided by the deviance in joint angle from touch-down to amortisation. All moment and stiffness measures were normalised to BW and leg length (vertical displacement from the greater trochanter to the floor whilst standing) and were therefore dimensionless.

The mean of each performance and stance phase measures were calculated for each athlete from the six athlete-specific trials. For the three age groups the group mean and standard deviation for each measure was subsequently determined from the individual mean values of each athlete assigned to the relevant group.

The time normalised (100 % of stance time) profiles of the vertical and anteroposterior ground contact forces and joint moments were examined between age-based groups to contextualise the discrete measures selected for statistical analysis. The individual stance phase profiles of the respective measures were interpolated to 101 points using a cubic spline (MathCad 13, Adept Scientific) to facilitate the calculation of each group mean (± standard deviation) continuous profiles for each measure throughout the stance phase.

A one-way analysis of variance (ANOVA) test was conducted to examine the age-based group differences in normally distributed discrete performance (velocity and step) and lower limb kinetic measures. The multiple comparisons (post hoc) statistical procedure, Tukey, was run to determine where the differences between the groups lay when a significant difference had been found from the ANOVA. The Shapiro-Wilk (Field, 2009) statistical test for normal distribution revealed that all measures were normally distributed except for the knee joint stiffness. A Mann Whitney U test was subsequently used to examine knee joint stiffness differences between each age group. An alpha-level of 0.05 was used for all inferential difference tests.

Effect sizes (Cohen, 1988) were calculated for each data set where significant differences were found between two or more of the groups. Cohen's d classification of effect size magnitude was used whereby $d < 0.19$ = negligible effect; $d = 0.20 – 0.49$ = small effect, $d = 0.50 – 0.79$ = moderate effect and $d > 0.8$ = large effect.

Results

The average whole body centre of mass anteroposterior running velocity and step length (Table I) were 0.80 m/s and 0.37 m slower and shorter, respectively ($p < 0.05$) for the M60 + group, than the S35 group. The running velocity, step length and step frequency were not significantly different between the M50 group when compared to the S35 and M60 + groups. The M60 + group produced a 0.046 s longer ($p < 0.05$) stance phase time (Figure 1) than the younger (S35) athletes.

As illustrated in Figure 1, a 0.41 BW ($p < 0.05$) and 0.71 BW ($p < 0.05$) lower maximal active vertical force and a 0.41 BW ($p < 0.05$) and 0.91 BW ($p < 0.05$) lower vertical force at amortisation was produced in the stance phases of the M50 and M60 + athletes respectively, when compared to the younger S35 athletes. The time of amortisation (Table I) occurred ($p < 0.05$) later in the stance phase for the M60 + group when compared to the S35 and M50 groups. The maximum braking and propulsive anteroposterior ground contact forces were lower for the M50 and M60 + groups when compared to the younger S35 athletes.

The lower limb kinetic analyses demonstrated the generation of a 32% and 42% lower ($p < 0.05$) ankle joint moment at amortisation by the M50 and M60 + groups, respectively when compared to the S35 group. As illustrated in Figure 2a, the older adult groups generated a lower ankle joint moment than the younger athletes for the duration of the stance phase (pre- and post-amortisation). While the knee and hip joint moments were typically lower across the stance phase duration for the older compared to the younger athletes (Figure 2b & 2c), the respective moments at amortisation were similar for each of the age-based athlete groups. In contrast, the knee joint stiffness was 71% ($p < 0.05$) lower for the M60 + group compared to the S35 group, while the ankle and hip stiffness were similar between the groups.

Discussion and implications

With increasing numbers of older athletes engaging in competitive athletic performances, the aim of this investigation was to examine and compare the lower limb kinetics of endurance running of younger and older athletes. The overall purpose of the study was to assist the development of customised coaching and training strategies for competitive master athletes.

Older master athletes (M60 +) were found to produce a slower (24%) mean self-selected running velocity when compared to younger (S35) male athletes. The inferior running performance of the M60 + group was simultaneously associated with the generation of a shorter step length (33%) than their S35 counterparts. While a simultaneous decline in step length and step frequency with age has previously been reported (Power et al., 2012; Cavagna et al., 2008) the performances of the older master athletes investigated in this study were achieved with a similar step frequency to the younger S35 group. The maintained step frequency combined with an extended stance time by the older athletes suggested the use of a compensatory reduced swing phase time across the step duration. Constraints in the ability to maintain the step length may subsequently be attributed in part, to constraints in the stance rather than swing phase mechanics of the ageing endurance athlete (Weyand, Sandell, Prime, & Bundle, 2010).

During the stance phase, the older athletes were further found to generate attenuated amortisation and active vertical ground contact forces when compared to the younger S35 athletes. Faster running speeds have previously been associated with greater ground contact (stance) support forces and the ability of the lower limb to generate maximum forces during ground contact (Weyand et al., 2000). The respective authors partially attributed the ability to generate large forces during ground contact to the force-velocity properties of the lower limb musculature. The attenuated ground contact forces and subsequent reduced running velocity evidenced for the older endurance athletes in this investigation may accordingly be indicative of an age-based inhibition or adaptation in the force-velocity function of the lower limb muscles.

Further examination of the normalised lower limb joint moment established the generation of a lower ankle moment but a similar knee joint moment in the older (M50 & M60 +) compared to the younger athletes. Lower joint moments in running have previously been associated with a reduced capacity to tolerate the applied load in stance (Kuitunen et al., 2002). Additional constraints in the ability of the older athletes to withstand the high support forces demanded in the pre-amortisation phase of stance provided a further indication of the effects of a declining force-velocity response of the joint musculature with age in competitively trained athletes. The continuous joint moment profiles simultaneously confirmed the production of a prominently reduced ankle joint moment pre- and post-amortisation by the older athletes when compared to the S35 athlete profile. Kuitunen et al. (2002) suggested an association between joint moment magnitudes and the efficiency to utilise stored elastic energy in sprint running. The reduced ankle joint moment generated during mid stance by the older athletes may subsequently be symptomatic of inhibitions in the distal joint musculature to utilise stored elastic energy and to generate high ground contact forces for whole body propulsion following amortisation. Extended consideration of the age-based conditioning of the ankle musculature in the training protocols of endurance athletes may provide a valuable approach to helping to maintain running performance in older competitive athletes.

In contrast to previous investigations of distance running mechanics in older athletes (e.g. Bus, 2003; Fukuchi & Duarte, 2008) this investigation extended the lower limb analyses to include whole limb and individual joint stiffness analyses during stance. Lower limb stiffness has previously been considered indicative of the ability to resist applied stretch (e.g. during impact) by the spring-like behaviour of the respective musculature (Kuitunen et al., 2002) and the study of muscle stiffness has been considered valuable for informing adaptation mechanisms in the human body (Wang, 2008; Günther & Blickhan, 2002; Lafortune, Hennig, & Lake, 1996). While similar ankle and hip joint stiffness values were evident in the pre-amortisation phase of the older (M50 & M60 +) athletes, a notably reduced pre-amortisation knee joint stiffness was generated by the oldest athletes.

Previous analyses of vertical jumping in older adults (Wang, 2008) similarly reported inhibited knee joint and maintained ankle and hip stiffness in older compared to younger adults. While Wang (2008) recruited untrained older adults, the correspondingly lower knee joint stiffness reported for the older, endurance-trained athletes in this investigation suggested that the ageing process, rather than disuse, may elicit a decline in the knee joint’s ability to tolerate applied stretching during dynamic movements. In contrast, similarities in the pre-amortisation ankle and hip joint stiffness between the age-based groups suggested the ankle and hip joint stiffness may be less prone to ageing effects, and that athletic training may not be fundamental in maintaining the respective joint musculature function. Since the direct quantification of soft tissue stiffness during dynamic movements is presently limited by the requirement to employ non-invasive techniques, an intervention study, where the effects of external factors such as surface stiffness are explicitly examined, may be warranted to provide further insight into the role of stiffness on a master athlete’s declining dynamic performance.

The ability of the ankle joint to tolerate and produce ground contact forces in early and mid stance respectively, and the knee joint to accommodate the applied stretching of the lower limb, may be suggested to contribute to the decline in step length and endurance running performance reported for the older athletes. In order to minimise the performance declines associated with ageing, competitive older endurance athletes may be encouraged to exploit training protocols that enhance the ankle and knee joints’ dynamic strength e.g. plyometric centred activities (Potach & Chu, 2000). Caution in prescribing age-based training programmes for competitive older endurance athletes must however be made due to the evidencing of athlete- rather than age-based responses in several lower limb kinetics such as ankle and hip stiffness.

Conclusion

The biomechanical comparison of the endurance running performances of older and younger competitive athletes suggested an ageing decline in running velocity that was underpinned by a shorter step length. The reduced step length by the older athlete was accompanied with limitations in the moments generated in the ankle and knee joints early in stance. Further longitudinal studies examining athlete- and age-based responses with changes in running performance are warranted in the future to extend insight into the mechanical influence of ageing on competitive endurance athletes.

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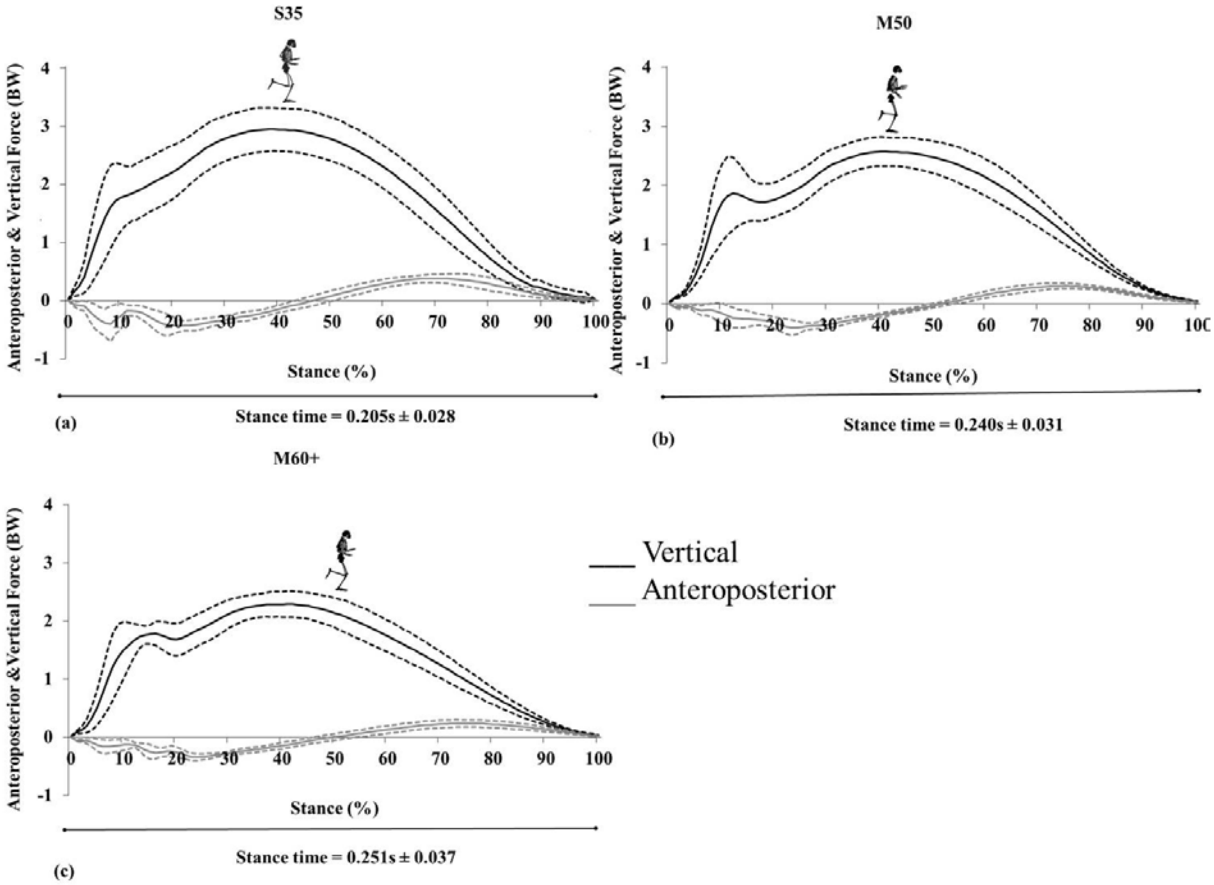
FIGURE 1. The age-based group mean (black/grey line) ± SD (dashed line) of the anteroposterior and vertical ground contact force time profiles of the stance phase. The stance phase duration is displayed below the anteroposterior axis. The animation figure represents the mean percentage time of stance of the instant of amortisation.

FIGURE 2. The age-based group mean (black line) ± standard deviation (dashed line) of the ankle (a), knee (b) and hip (c) sagittal plane moment time profiles of the stance phase.



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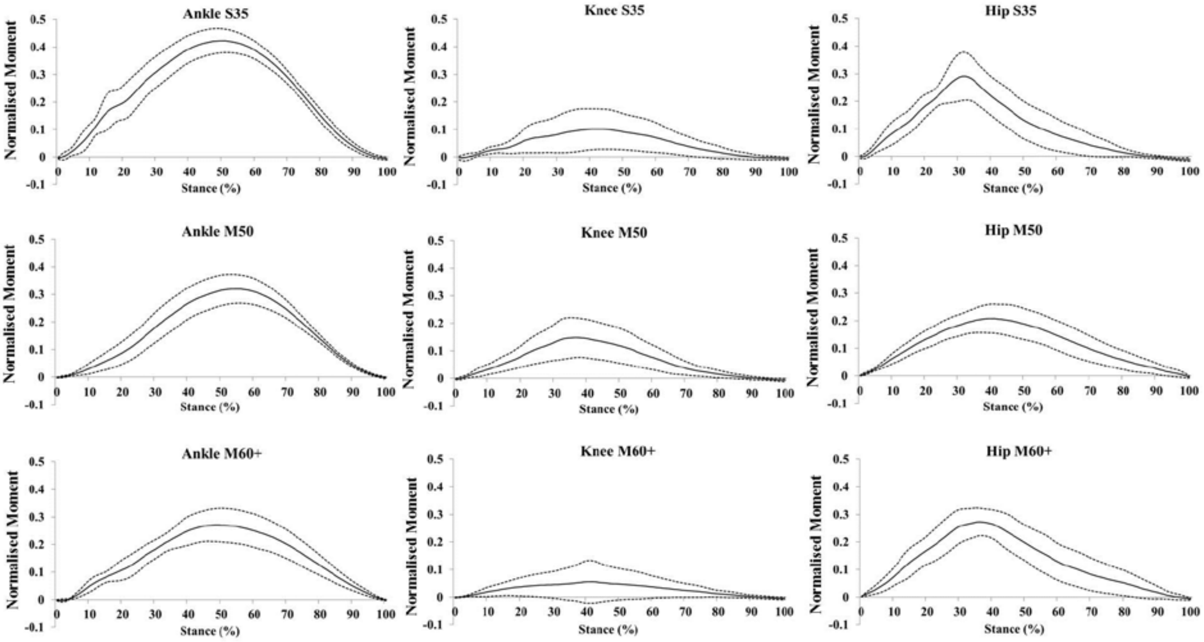

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TABLE I. Summary of the measures for each group (M ± SD).

	Measure	**S35 (26-32 years)**	**M50 (50-54 years)**	**M60+ (60-68 years)**
†	Running velocity (m/s)	4.13 ± 0.54	3.75 ± 0.46	3.34 ± 0.40
†	Step length (m)	1.52 ± 0.22	1.35 ± 0.21	1.14 ± 0.13
	Step frequency (Hz)	2.75 ± 0.20	2.81 ± 0.27	2.95 ± 0.24
	Peak vertical force (BW)	2.21 ± 0.71	2.18 ± 0.56	1.94 ± 0.41
♦†	Maximal active vertical force (BW)	3.02 ± 0.36	2.61 ± 0.25	2.31 ± 0.20
♦†◘	Vertical force at amortisation (BW)	2.96 ± 0.41	2.54 ± 0.25	2.05 ± 0.25
	Time to maximal active vertical force (%)	41 ± 4	42 ± 4	40 ± 4
†◘	Time to amortisation (%)	44 ± 2	45 ± 3	53 ± 4
♦†	Maximal negative horizontal force (BW)	0.71 ± 0.30	0.47 ± 0.11	0.41 ± 0.11
♦†	Maximal positive horizontal force (BW)	0.41 ± 0.08	0.31 ± 0.05	0.25 ± 0.07
	Change in normalised lower body compression	0.08 ± 0.01	0.06 ± 0.02	0.08 ± 0.04
	Normalised lower body stiffness	40.03 ± 9.03	49.71 ± 15.59	34.84 ± 17.19
♦†	Normalised ankle moment	0.38 ± 0.05	0.26 ± 0.06	0.22 ± 0.05
	Normalised knee moment	0.13 ± 0.11	0.12 ± 0.06	0.04 ± 0.04
	Normalised hip moment	0.16 ± 0.06	0.17 ± 0.06	0.13 ± 0.03
	Normalised ankle stiffness x 10^{-2} ($^{o\,-1}$)	1.50 ± 0.44	2.22 ± 1.30	1.76 ± 1.09
†	Normalised knee stiffness x 10^{-2} ($^{o\,-1}$)	0.56 ± 0.50	0.37 ± 0.25	0.16 ± 0.19
	Normalised hip stiffness x 10^{-2} ($^{o\,-1}$)	1.80 ± 0.72	2.37 ± 2.02	1.38 ± 0.54

♦ significant difference between S32 and M50 ($p < 0.05$); † significant difference between S32 and M60+ ($p < 0.05$); ◘ significant difference between M50 and M60+ ($p < 0.05$). Cohen's d ranged from 1.35 to 3.46 indicating large differences between the group means for those where statistical significance lay.