Journal of Sports Sciences, November 2008; 26(13): 1447–1454

Routledge
Taylor & Francis Group

Comparison of three-dimensional lower extremity running kinematics of young adult and elderly runners

REGINALDO K. FUKUCHI[1] & MARCOS DUARTE[2]

[1]*Laboratory of Biomechanics, Instituto Vita, São Paulo and* [2]*Escola de Educação Fisica e Esporte, University of São Paulo, São Paulo, Brazil*

(Accepted 16 May 2008)

Abstract

The objective of this study was to compare the three-dimensional lower extremity running kinematics of young adult runners and elderly runners. Seventeen elderly adults (age 67–73 years) and 17 young adults (age 26–36 years) ran at $3.1\ \text{m} \cdot \text{s}^{-1}$ on a treadmill while the movements of the lower extremity during the stance phase were recorded at 120 Hz using three-dimensional video. The three-dimensional kinematics of the lower limb segments and of the ankle and knee joints were determined, and selected variables were calculated to describe the movement. Our results suggest that elderly runners have a different movement pattern of the lower extremity from that of young adults during the stance phase of running. Compared with the young adults, the elderly runners had a substantial decrease in stride length (1.97 vs. 2.23 m; $P = 0.01$), an increase in stride frequency (1.58 vs. 1.37 Hz; $P = 0.002$), less knee flexion/extension range of motion (26 vs. 33°; $P = 0.002$), less tibial internal/external rotation range of motion (9 vs. 12°; $P < 0.001$), larger external rotation angle of the foot segment (toe-out angle) at the heel strike (-5.8 vs. $-1.0°$; $P = 0.009$), and greater asynchronies between the ankle and knee movements during running. These results may help to explain why elderly individuals could be more susceptible to running-related injuries.

Keywords: *Ageing, biomechanics, running, exercise*

Introduction

With the increase in life expectancy and the benefits that regular physical activity bring to health (Young & Dinan, 2005), there has been an increase in the number of elderly people engaged in recreational and competitive running. However, there is concern that the incidence of injury among older runners is greater than that among young adult runners (Marti, Vader, Minder, & Abelin, 1988; McKean, Manson, & Stanish, 2006), and that older runners take longer to recover from an injury and so take longer to return to physical activity (Matheson, Macintyre, Taunton, Clement, & Lloyd-Smith, 1989).

The greater incidence of injury and the delayed return to running in the elderly population may be partly due to degeneration of the musculoskeletal system arising from ageing, and partly due to differences in running movement patterns between elderly and young adult runners (Bus, 2003; Matheson *et al.*, 1989; McKean *et al.*, 2006). Age-related changes in the musculoskeletal system, such as increased joint stiffness and reduced function of the triceps surae and quadriceps femoris muscle-tendon units, have been observed by Karamanidis and Arampatzis (2005) and by Trappe (2007), but relatively little is known about the movement patterns of elderly runners. We do know that elderly runners have a shorter stride length and less knee flexion/extension range of motion (Conoboy & Dyson, 2006; Karamanidis & Arampatzis, 2005). Furthermore, we know that older runners (aged between 55 and 65 years, but not yet elderly) show no differences from young adult runners in the kinematics of the ankle region, but have more knee flexion at heel strike, less knee flexion/extension range of motion, a higher impact peak force, and a higher initial loading rate (Bus, 2003).

Knowledge of how elderly people run may lead to recommendations for running training to reduce the risk and severity of injury, and may aid the development of appropriate running shoes for this population. Therefore, the objective of the present study was to compare the three-dimensional kinematics of the lower extremity of young adult runners and elderly runners during the stance phase of running.

Correspondence: M. Duarte, Escola de Educacão Fisica e Esporte, USP, Av. Mello Moraes 65, Cidade Universitária, CEP 05508-030, Sao Paulo, SP, Brazil. E-mail: mduarte@usp.br

ISSN 0264-0414 print/ISSN 1466-447X online © 2008 Taylor & Francis
DOI: 10.1080/02640410802209018

Methods

Participants

Seventeen elderly male runners (mean age 69 years, $s = 2$, range 67–73; height 1.68 m, $s = 0.05$; mass 65 kg, $s = 9$ kg) and 17 young adult male runners (mean age 31 years, $s = 6$, range 22–39; height 1.73 m, $s = 0.07$; mass 73 kg, $s = 9$ kg) volunteered to participate in the study. The elderly runners were significantly lighter ($P = 0.02$) and shorter ($P = 0.02$) than the young adult runners, and all participants competed in amateur long-distance races. The inclusion criteria required the participants not to use any kind of orthosis, to run at least three times per week with a total weekly distance of more than 20 km, to be rearfoot strikers during running, and to achieve a reported time of less than one hour for a recent 10-km running event. The exclusion criteria were any incidences of injury in the 3 months prior to the experiment, and musculoskeletal alterations in the lower limbs that could affect the biomechanics of running (such as flat foot or knee valgus, among others). This study was approved by the Ethics Committee of the School of Physical Education and Sport at the Univeristy of São Paulo.

Procedures

The participants were filmed while running on a motor-driven treadmill (Inbrasport, Porto Alegre, Brazil) at $3.1\ \mathrm{m \cdot s^{-1}}$ and no inclination. The participants warmed up, then ran on the treadmill for a few minutes to become familiar with it. The participants then ran at increasing speed until the desired $3.1\ \mathrm{m \cdot s^{-1}}$ speed was reached (typically about 10 min after the participant first started running on the treadmill). After a further 5 min of running at $3.1\ \mathrm{m \cdot s^{-1}}$, at least five consecutive steps of the right leg were recorded by the video cameras for analysis. The treadmill speed was controlled and remained constant for both groups, and was comfortable for all participants. The participants were required to wear their own running shoes that they normally used for training because forcing participants to wear unfamiliar shoes could have affected their normal movement pattern during running. Twenty-nine of the 34 participants wore neutral running shoes (i.e. no anti-pronation or anti-supination elements in the outsole), and there were no noticeable differences among the running shoes in heel height, weight or sole hardness.

Kinematics measurements

To record the three-dimensional kinematics of the lower extremity, we used the Calibrated Anatomical System Technique (CAST) experimental protocol developed by Cappozzo and colleagues (Cappozzo, Catani, Croce, & Leardini, 1995). With this protocol, rigid clusters with retro-reflective markers are used to measure the motion of each segment of interest. A calibration trial was performed in which the participant stood in a neutral posture with both cluster and bony anatomical landmark markers on the right leg, as shown in Figure 1. Following the calibration trial, the running trials were performed with only the rigid clusters. All markers on the shoe were positioned by estimating their corresponding position on the foot by palpation.

The axes and planes of the anatomical coordinate systems were determined according to Cappozzo, Catani, Croce and Leardini (1995) and Grood and Suntay (1983). For the definition of the joint axes, it was necessary to determine the hip, knee, and ankle joint centres. The hip joint centre was determined using a predictive method based on the relative position of anatomical landmarks (Bell, Pedersen, & Brand, 1990). The knee and ankle joint centres were determined as the mean point between the femur epicondyles and the lateral and medial malleolus, respectively. The rotations about the knee and rearfoot in all anatomical planes (frontal, sagittal, and transverse) were calculated. In particular, we used the tibial rotation (the movement between tibia and foot), instead of abduction/adduction, to report the foot movements in the transverse plane because the tibial rotation better represents the coupling between foot and shank during the stance phase of running (Nigg, Cole, & Nachbauer, 1993). All angles were referenced to the angle values during standing, with the exception of inversion/eversion of the rearfoot. A zero reference for inversion/eversion was defined when the vertical axes of the calcaneus

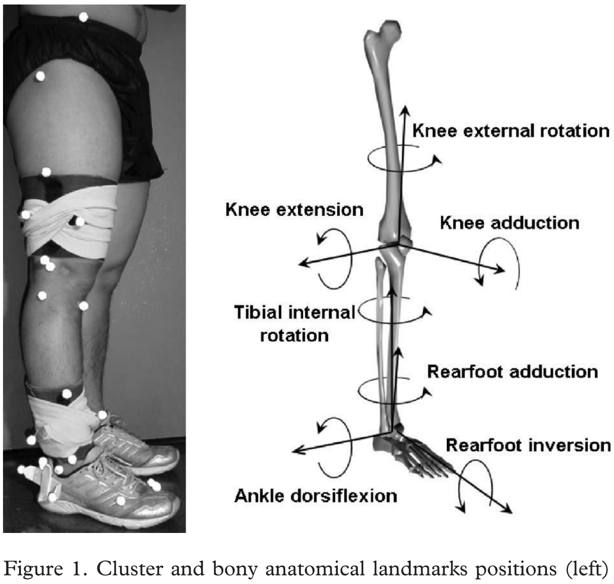

Figure 1. Cluster and bony anatomical landmarks positions (left) and angle convention (right).

and tibia were parallel, a procedure similarly employed in other studies (McClay & Manal, 1997, 1998a). In addition to the joint angles, we investigated the absolute segmental angles of rotation of the femur, tibia, and foot. These angles were measured between the anterior axes of each segment reference system and the laboratory (global) reference system.

Kinematic data were recorded and digitized at 120 Hz using four digital cameras (GR-DVL9800U, JVC Inc., Wayne, NJ, USA). The four cameras were synchronized using a simultaneous sound event in their sound channel. We analysed five consecutive support periods of the right foot for each runner. The digitization of the marker positions was performed using APAS software (Ariel Dynamics, Inc., Trabuco Canyon, CA, USA). The three-dimensional reconstruction of the marker positions using the Direct Linear Transformation procedure and all data processing and analyses were performed in MATLAB 6.5 (Mathworks Inc., Natick, MA, USA). The data were smoothed with a 20-Hz low-pass Butterworth filter of fourth order and zero lag. The average root-mean-square error of the three-dimensional reconstruction was 3.3 mm.

Data analysis

The present study is the first to investigate the three-dimensional kinematics of the lower extremity of elderly runners. For a better characterization of the elderly group, we selected the main variables commonly reported in similar studies on young adults (McClay & Manal, 1998a, 1998b; Pohl, Messenger, & Buckley, 2007). The following variables were selected: stride length and stride frequency; initial contact, peak and range of motion angles; and percentage of stance to peak of rearfoot eversion, knee internal rotation, and knee flexion. The ratio between the rearfoot eversion and tibial internal rotation range of motions was used to investigate the coupling between rearfoot and knee movements. We also quantified the rotational angles of the femur, tibia, and foot segments during the heel strike at the global coordinate system referenced to the neutral position during standing.

The support periods of the trials were normalized in time from 0 to 100% in increments of 1%. These periods were then averaged to obtain the mean support period for each participant, and the same process was repeated to obtain the mean and standard deviation of the support period among participants. The normality and homogeneity of variances in the data were verified with the Shapiro-Wilk test and the Levene statistic, respectively. Unpaired *t*-tests were used to determine the effect of ageing on kinematic variables. Pearson's correlation analyses were employed to assess the relation between some of the variables. The rotational angles were analysed using a 2 × 3 analysis of variance (ANOVA), with age (young adult runners vs. elderly runners) as a between-participants factor and segment (femur vs. tibia vs. foot) as a within-participant factor. *Post hoc* comparisons were performed using pair-wise comparisons with Bonferroni adjustment (the *P*-values shown for the *post hoc* comparisons are the raw *P*-values multiplied by the number of tests carried out). A 0.05 level of significance was adopted in all statistical tests, which were performed using SPSS 12 (SPSS Inc., Chicago, IL, USA).

Results

Figure 2 shows the time-series of the three-dimensional kinematics of the rearfoot and knee joints averaged across participants for the young adult and elderly groups running at 3.1 $m \cdot s^{-1}$. Table I shows the mean and standard deviation values and the statistics for the comparisons between the two groups for the analysed variables. Elderly runners exhibited a decrease in stride length ($P < 0.001$) and an increase in stride frequency ($P = 0.01$) compared with the young adults during running at 3.1 $m \cdot s^{-1}$. The participants' heights were significantly

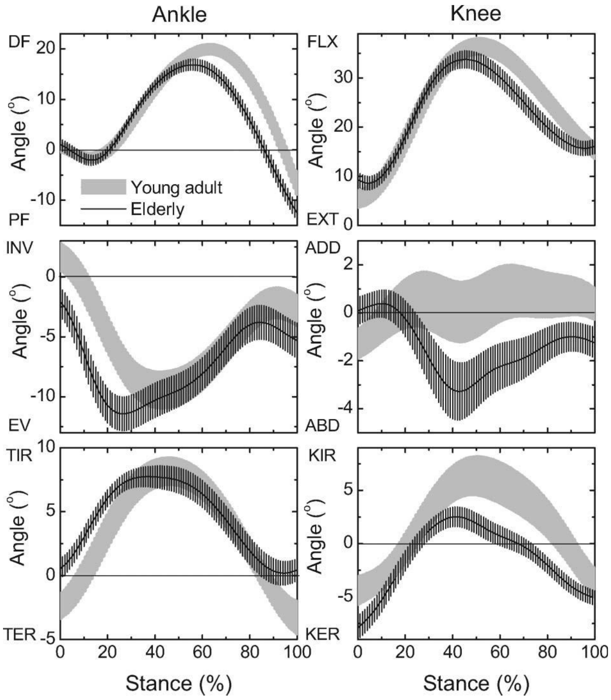

Figure 2. Mean (and standard error) time-series of the three-dimensional kinematics of the ankle and knee joints across participants for the young adult runners and elderly runners during the stance period of running at 3.1 $m \cdot s^{-1}$. DF = dorsiflexion, PF = plantarflexion, INV = inversion, EV = eversion, TIR = tibial internal rotation, TER = tibial external rotation, FLX = flexion, EXT = extension, ADD = adduction, ABD = abduction, KIR = knee internal rotation, KER = knee external rotation.

Table I. Mean values ($\pm s$) of the analysed kinematic variables for the young adults and elderly participants during the stance period of running at $3.1\ \text{m} \cdot \text{s}^{-1}$, and the *P*-values of the *t*-test comparisons between groups

Variable	Young adults	Elderly adults	*P*
Stride parameters			
Stride length (m)	2.23 ± 0.12	1.97 ± 0.25	< 0.001*
Stride frequency (Hz)	1.37 ± 0.07	1.58 ± 0.32	0.01*
Initial contact angle (°)			
Rearfoot dorsiflexion/ plantarflexion	0 ± 2	0 ± 5	0.93
Rearfoot eversion/ inversion	2 ± 4	−1 ± 6	0.12
Tibial internal/ external rotation	−2 ± 3	0 ± 3	0.07
Knee flexion/extension	5 ± 6	10 ± 6	0.04*
Knee adduction/ abduction	−1 ± 2	0 ± 2	0.09
Knee internal/ external rotation	−4 ± 5	−8 ± 4	0.05
Peak angle (°)			
Rearfoot dorsiflexion	20 ± 3	18 ± 5	0.13
Rearfoot eversion	−10 ± 6	−12 ± 6	0.49
Tibial internal rotation	9 ± 3	9 ± 3	0.96
Knee flexion	37 ± 5	35 ± 7	0.30
Knee adduction	2 ± 4	0 ± 3	0.06
Knee abduction	−1 ± 4	−5 ± 5	0.06
Knee internal rotation	7 ± 7	4 ± 3	0.06
Range of motion angle (°)			
Rearfoot dorsiflexion/ plantarflexion	23 ± 4	22 ± 2	0.36
Rearfoot eversion/ inversion	12 ± 4	11 ± 3	0.16
Tibial internal/ external rotation	12 ± 2	9 ± 2	0.002*
Knee flexion/extension	33 ± 5	26 ± 3	< 0.001*
Knee adduction/ abduction	4 ± 2	4 ± 3	0.47
Knee internal/ external rotation	12 ± 8	11 ± 4	0.61
Time to peak (% of stance)			
Rearfoot eversion	41 ± 10	33 ± 10	0.02*
Tibial internal rotation	44 ± 12	44 ± 12	0.98
Knee flexion	51 ± 7	50 ± 4	0.46
Knee internal rotation	46 ± 15	46 ± 8	1.0
Coupling parameter			
Eversion/tibial internal rotation ratio	1.1 ± 0.3	1.2 ± 0.4	0.27

*Significant difference ($P < 0.05$) of unpaired comparison between groups.

correlated with their stride lengths for the young adult runners ($r = 0.55$, $P = 0.02$) and not correlated for the elderly runners ($r = -0.05$, $P = 0.85$). There was no significant correlation between participants' heights and their stride lengths when the two groups were combined ($r = 0.34$, $P = 0.05$).

The rearfoot dorsiflexion showed a very similar pattern between the two groups. Upon landing (heel strike), the ankle displayed a small dorsiflexion (close to the neutral position), followed by some small plantarflexion, and rapidly moved to a marked dorsiflexion, reaching a maximum between 50 and 60% of the stance phase, before finally moving into plantarflexion at the end of the support phase (toe-off). The only noticeable difference between the two groups was that the elderly group reached maximum dorsiflexion 10% earlier than the young adult group, and consequently the plantarflexion movement was initiated first for the elderly group. In the frontal plane, the movement patterns of the rearfoot joint were also similar between the two groups. However, the young adult runners landed in rearfoot inversion and rapidly moved to eversion with a maximum at approximately 40% of the stance phase, while the elderly runners had already landed in rearfoot eversion and reached maximum eversion 10% earlier than the young adults. In the transverse plane, the young adult runners landed with the tibia in external rotation, moving to internal rotation at the middle of the stance phase, before returning again to external rotation at toe-off. The elderly group displayed a similar pattern. However, they had already landed with tibial internal rotation and never displayed tibial external rotation. Because of this, the tibial rotation range of motion of the elderly group was lower than that of the young adult group ($P = 0.002$).

The knee flexion/extension pattern was similar between the two groups: both groups landed with a small flexion, increased this flexion to reach a peak at 50% of the stance phase, and then terminated the stance phase with a lower flexion. However, the elderly group showed lower knee flexion/extension range of motion than the young adult group ($P < 0.001$). This decreased knee flexion/extension range of motion was not correlated with the stride length, neither within groups ($r = -0.28$, $P = 0.28$ for the young adults; $r = -0.29$, $P = 0.26$ for the elderly adults), nor with the groups combined ($r = 0.21$, $P = 0.24$). In the frontal plane, the adduction/abduction knee angle was the only time-series that presented a different pattern between the two groups. The young adult runners landed with a small knee abduction to rapidly move to a small adduction, while the elderly runners landed with a small knee adduction to rapidly move to abduction – the opposite of the young adult runners. However, these results must be interpreted with caution as both groups had an adduction/abduction angle range of motion of only 4° and there was great variability among participants. In the transverse plane, the patterns were also similar between the two groups; both groups landed with the knee externally rotated, moving to internal rotation in the middle of the stance phase, before terminating the stance phase at external rotation of the knee again. At heel strike, the elderly runners had a tendency (although not statistically significant) for greater knee external rotation than the young adult runners ($P = 0.05$).

Figure 3 compares plots of mean rearfoot eversion angle versus mean knee rotation angle, knee flexion, and mean tibial rotation for the two groups. When the percentage of stance to peak for these variables were compared within the groups (see Table I for the mean values), we observed that the rearfoot eversion peak significantly preceded the knee flexion peak only for the elderly runners (see Figure 3b; $P = 0.007$), while the rearfoot eversion peak significantly preceded the knee internal rotation peak for the young adult runners as well as for the elderly runners (see Figure 3a; $P = 0.03$ and $P < 0.001$, respectively). However, a comparison of the two related asynchronies in the two groups (the difference between the times to peak of rearfoot eversion and knee flexion and the difference between the times to peak of rearfoot eversion and knee internal rotation) showed no significant difference between young adult and elderly runners ($P = 0.08$ and $P = 0.35$, respectively).

Figure 4 shows the values for the rotational angles of the femur, tibia, and foot segments during the heel strike at the global coordinate system referenced to the neutral position during standing for the young adult runners (femur: mean $-2.4°$, $s = 6.2$; tibia: mean $-6.3°$, $s = 5.3$; and foot: mean $-1.0°$, $s = 5.0$) and for the elderly runners (femur: mean $-1.6°$, $s = 6.2$; tibia: mean $-8.9°$, $s = 5.6$; and foot: mean $-5.8°$, $s = 5.1$). The ANOVA yielded a significant interaction effect between age and segment ($F_{2,31} = 7.1$, $P = 0.002$). The *post hoc* test revealed that the tibia rotated externally significantly more than the femur and foot segments for both young adult runners ($P = 0.001$ and $P < 0.001$, respectively) and elderly runners ($P < 0.001$ and $P = 0.006$, respectively). For the elderly runners, there was also a significant increase in external rotation for the foot segment compared with the femur segment ($P = 0.007$). Finally, the *post hoc* test also revealed that the foot segment rotated externally significantly more for the elderly runners than for the young adult runners ($P = 0.009$).

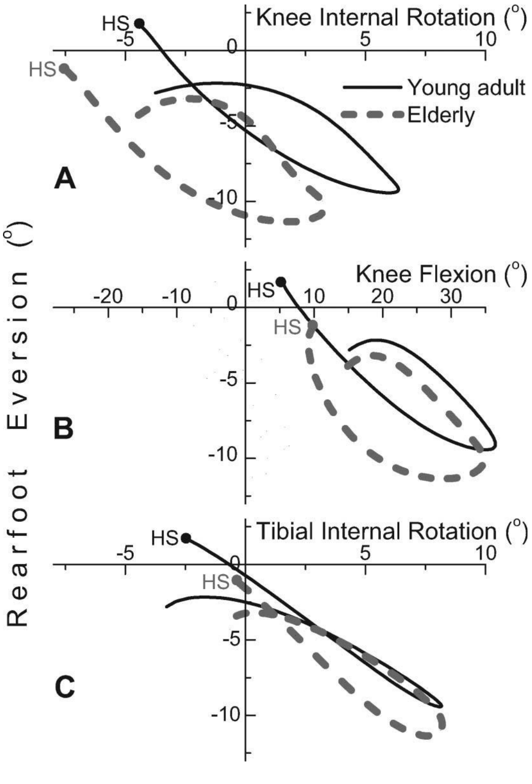

Figure 3. Mean angles of knee internal rotation (A), knee flexion (B), and tibial internal rotation (C) versus the mean angle of rearfoot eversion during the stance period of running at 3.1 m · s^{-1} by young adult runners and elderly runners. HS = heel strike.

Discussion

We compared the kinematics of young adult and elderly runners running on a treadmill at 3.1 m · s^{-1}. We chose a treadmill instead of overground running to better control the running speed of the participants. Whether running on a treadmill is different from overground running is controversial. Although van Ingen Schenau (1980) showed that both conditions are mechanically equivalent, and Cunningham and Perry (2007) noted no difference for the rearfoot kinematics, Nigg and colleagues (Nigg, De Boer, & Fisher, 1995) reported that runners systematically plant their feet in a flatter position on the treadmill than in overground running. Most likely, any differences between

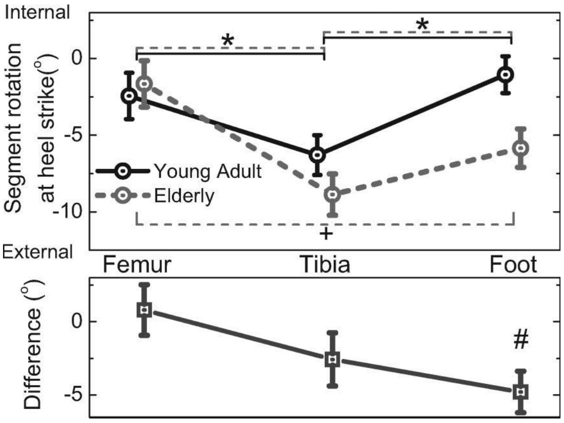

Figure 4. Mean (and standard error) rotation angle during the heel strike at the global coordinate system for the femur, tibia, and foot segments for the young adult and elderly groups of runners, and the between-group difference. Significant ($P < 0.05$) segment difference for both groups (*) and for the elderly runners only (+). Significant age difference (#).

treadmill and overground running are due to the different mechanical properties of the surfaces, rather than the activity itself. Overall, the kinematic data for the young adult runners in the present study are similar to those for overground running reported in previous studies (Ferber, Davis, & Williams, 2003; McClay & Manal, 1998a).

We observed that the elderly runners ran on the treadmill with a shorter stride length than the young adult runners. Although the elderly runners were on average 0.05 m shorter than the young adults, there was no significant correlation between the participants' height and their stride length when considering both groups together. Such a decrease in stride length in older aged and elderly runners has been reported elsewhere for overground running (Bus, 2003; Conoboy & Dyson, 2006). However, some researchers (Bus, 2003; Cavanagh & Williams, 1982) have also observed a lack of correlation between stride length and body height. Because of this, we did not scale the kinematic data to body height. Recent data suggest that a decrease in stride length and increase in step frequency in elderly runners is caused by force reduction in old age (Cavagna, Legramandi, & Peyre-Tartaruga, 2008).

Knee kinematics

Elderly runners exhibited a higher knee flexion at heel strike and lower flexion/extension range of motion of the knee than the young adults. Bus (2003) reported similar findings for older adults (55–65 years), and Karamanidis and Arampatzis (2005) also reported lower flexion/extension range of motion of the knee in older aged men (60–69 years) compared with young adults during running. A tendency for a decline of the joint range of motion in the majority of knee and rearfoot movements was observed in the present study, although only the knee flexion/extension angle presented a significant decrease in joint mobility in elderly runners. The decreased knee flexion/extension range of motion was not correlated with the stride length within groups or across groups. The observed reduction in the knee joint range of motion and shorter stride length in the elderly runners may be due to an increase in ankle and knee joint stiffness with ageing, or due to the reduced strength of the triceps surae and quadriceps femoris muscle-tendon units that occurs with ageing, which have been observed in elderly individuals (Karamanidis & Arampatzis, 2005).

Ankle and foot kinematics

A main focus of the present study was on rearfoot motion because excessive pronation of the rearfoot joint has often been associated with musculoskeletal injuries in runners (Hintermann & Nigg, 1998). Contrary to our expectations, there was no difference for this angle between the two groups. This absence of an age-related difference has been observed previously by Bus (2003) for runners aged 55–65 years. However, in the present study the time to peak of rearfoot eversion was significantly shorter for the elderly runners, which may suggest higher strain rates on the musculoskeletal system. This higher velocity (the range of motion was the same for both groups) of rearfoot eversion has been related to the incidence of running injuries (see, for example, Messier & Pittala, 1988; Smith, Clarke, Hamill, & Santopietro, 1986), although one study did not observe this relation (Hreljac, Marshall, & Hume, 2000). This result suggests that elderly runners might possibly be more susceptible to injuries of the ankle than young adults; however, further studies focusing on running-related injuries in elderly individuals are required to investigate this relation.

A greater abduction of the foot in the global reference system (known as toe-out angle) for elderly individuals compared with young adults during walking has been widely reported (McClay & Manal, 1998a; Wang, Kuo, Andriacchi, & Galante, 1990), and it has been viewed as a compensatory strategy to reduce the knee adduction moment (Chang *et al.*, 2007; Wang *et al.*, 1990). We also observed an increased toe-out angle in elderly individuals during running, possibly because the elderly individuals adopted the same compensatory strategy observed while walking.

One main concern in the development of running shoes is to provide movement control of the rearfoot as well as shock-absorption during the stance phase to decrease excessive pronation (eversion) and avoid such running-related injuries of the lower extremity. [See Hintermann and Nigg (1998) for a description of the aetiology of running injuries related to rearfoot pronation.] In the present study, the participants wore their own running shoes; however, all shoes had similar heel height, weight, and sole hardness, and 85% of the shoes were neutral (i.e., no anti-pronation or anti-supination elements in the outsole). The observed lack of statistical differences in the rearfoot kinematics between elderly and young adult runners suggests that it is not necessary to adapt running shoes so as to accommodate possible age differences in eversion kinematics.

Knee–ankle coupling

During the stance phase of running, a rotation of the tibia at the transverse plane occurs (DeLeo, Dierks, Ferber, & Davis, 2004; McClay & Manal, 1997) and we observed a significant decrease of this range of motion in the elderly runners compared with the young adult runners. It would appear that the cause of the reduction in the range of motion of the tibial rotation in the elderly runners was the greater tibial internal rotation at the heel strike for these participants (although the between-group difference of the tibial internal rotation angle at the heel strike was only close to being significant: $P = 0.07$). Even though there was a decrease in the tibial internal rotation range of motion, no between-group difference in the eversion/tibial internal rotation ratio was found; this latter result has also been observed for young adults (McClay & Manal, 1997; Stacoff *et al.*, 2000).

After the peak of rearfoot eversion, the rearfoot starts to invert, causing external rotation of the tibia. During knee flexion, a reverse mechanism is observed: with the flexion of the knee an internal rotation of the tibia is observed, which is known as the screw-home mechanism (Ramsey & Wretenberg, 1999). Therefore, when rearfoot inversion occurs before knee extension, it leads to a ‘‘mechanical dilemma’’ at the knee, which may result in injury (DeLeo *et al.*, 2004). We observed that the elderly runners showed greater asynchronies between the instant where the peaks of the rearfoot eversion and knee flexion and between the peaks of the rearfoot eversion and knee internal rotation occurs. Such asynchronies have been reported in other studies of young adult runners, and it has been suggested that larger asynchronies could increase the risk of injury (McClay & Manal, 1997; Nigg *et al.*, 1993; Stergiou, Bates, & James, 1999). Therefore, it is possible that the elderly runners, with greater asynchronies between the times to peak of rearfoot eversion, knee flexion, and knee internal rotation, are potentially more susceptible to injury than young adults.

In this study, we investigated young adult and elderly recreational runners. Unfortunately, this is only a small proportion of the young adult population and a much smaller proportion of the elderly population. The present results cannot be generalized to sedentary or occasional runners, let alone sedentary elderly individuals.

Conclusion

The differences observed in the present study suggest that elderly runners have a movement pattern of the lower extremity that is different from that of young adult runners during the stance phase of running, and this may help to explain why elderly individuals could be more susceptible to running-related injuries. It is thus important to investigate to what extent these differences are related to the incidence of injuries in elderly runners, and how many of these differences reflect age-related musculoskeletal changes or compensatory strategies adopted by the elderly runners.

Acknowledgements

This work was supported by a grant (04/10917-0) from Fundacão de Amparo à Pesquisa do Estado de São Paulo – FAPESP/Brazil awarded to Marcos Duarte.

References

Bell, A. L., Pedersen, D. R., & Brand, R. A. (1990). A comparison of the accuracy of several hip center location prediction methods. *Journal of Biomechanics*, *23*, 617–621.

Bus, S. A. (2003). Ground reaction forces and kinematics in distance running in older-aged men. *Medicine and Science in Sports and Exercise*, *35*, 1167–1175.

Cappozzo, A., Catani, F., Croce, U. D., & Leardini, A. (1995). Position and orientation in space of bones during movement: Anatomical frame definition and determination. *Clinical Biomechanics*, *10*, 171–178.

Cavagna, G. A., Legramandi, M. A., & Peyre-Tartaruga, L. A. (2008). Old men running: Mechanical work and elastic bounce. *Proceedings of the Royal Society of London B*, *275*, 411–418.

Cavanagh, P. R., & Williams, K. R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise*, *14*, 30–35.

Chang, A., Hurwitz, D., Dunlop, D., Song, J., Cahue, S., Hayes, K. *et al.* (2007). The relationship between toe-out angle during gait and progression of medial tibiofemoral osteoarthritis. *Annals of the Rheumatic Diseases*, *66*, 1271–1275.

Conoboy, P., & Dyson, R. (2006). Effect of aging on the stride pattern of veteran marathon runners. *British Journal of Sports Medicine*, *40*, 601–604.

Cunningham, E. A., & Perry, S. D. (2007). Rearfoot kinematic differences between level treadmill and level ground running. *Journal of Biomechanics*, *40*, S515.

DeLeo, A. T., Dierks, T. A., Ferber, R., & Davis, I. S. (2004). Lower extremity joint coupling during running: A current update. *Clinical Biomechanics*, *19*, 983–991.

Ferber, R., Davis, I. M., & Williams, D. S., III (2003). Gender differences in lower extremity mechanics during running. *Clinical Biomechanics*, *18*, 350–357.

Grood, E. S., & Suntay, W. J. (1983). A joint coordinate system for the clinical description of three-dimensional motions: Application to the knee. *Journal of Biomechanical Engineering*, *105*, 136–144.

Hintermann, B., & Nigg, B. M. (1998). Pronation in runners: Implications for injuries. *Sports Medicine*, *26*, 169–176.

Hreljac, A., Marshall, R. N., & Hume, P. A. (2000). Evaluation of lower extremity overuse injury potential in runners. *Medicine and Science in Sports and Exercise*, *32*, 1635–1641.

Karamanidis, K., & Arampatzis, A. (2005). Mechanical and morphological properties of different muscle-tendon units in the lower extremity and running mechanics: Effect of aging and physical activity. *Journal of Experimental Biology*, *208*, 3907–3923.

Marti, B., Vader, J. P., Minder, C. E., & Abelin, T. (1988). On the epidemiology of running injuries: The 1984 Bern Grand-Prix study. *American Journal of Sports Medicine*, *16*, 285–294.

Matheson, G. O., Macintyre, J. G., Taunton, J. E., Clement, D. B., & Lloyd-Smith, R. (1989). Musculoskeletal injuries associated with physical activity in older adults. *Medicine and Science in Sports and Exercise*, *21*, 379–385.

McClay, I., & Manal, K. (1997). Coupling parameters in runners with normal and excessive pronation. *Journal of Applied Biomechanics*, *13*, 109–124.

McClay, I., & Manal, K. (1998a). A comparison of three-dimensional lower extremity kinematics during running between excessive pronators and normals. *Clinical Biomechanics*, *13*, 195–203.

McClay, I., & Manal, K. (1998b). The influence of foot abduction on differences between two-dimensional and three-dimensional rearfoot motion. *Foot and Ankle International*, *19*, 26–31.

McKean, K. A., Manson, N. A., & Stanish, W. D. (2006). Musculoskeletal injury in the masters runners. *Clinical Journal of Sport Medicine*, *16*, 149–154.

Messier, S. P., & Pittala, K. A. (1988). Etiologic factors associated with selected running injuries. *Medicine and Science in Sports and Exercise*, *20*, 501–505.

Nigg, B. M., Cole, G. K., & Nachbauer, W. (1993). Effects of arch height of the foot on angular motion of the lower extremities in running. *Journal of Biomechanics*, *26*, 909–916.

Nigg, B. M., De Boer, R. W., & Fisher, V. (1995). A kinematic comparison of overground and treadmill running. *Medicine and Science in Sports and Exercise*, *27*, 98–105.

Pohl, M. B., Messenger, N., & Buckley, J. G. (2007). Forefoot, rearfoot and shank coupling: Effect of variations in speed and mode of gait. *Gait and Posture*, *25*, 295–302.

Ramsey, D. K., & Wretenberg, P. F. (1999). Biomechanics of the knee: Methodological considerations in the *in vivo* kinematic analysis of the tibiofemoral and patellofemoral joint. *Clinical Biomechanics*, *14*, 595–611.

Smith, L. S., Clarke, T. E., Hamill, C. L., & Santopietro, F. (1986). The effects of soft and semi-rigid orthoses upon rearfoot movement in running. *Journal of the American Podiatric Medical Association*, *76*, 227–233.

Stacoff, A., Nigg, B. M., Reinschmidt, C., van den Bogert, A. J., Lundberg, A., Stussi, E. *et al.* (2000). Movement coupling at the ankle during the stance phase of running. *Foot and Ankle International*, *21*, 232–239.

Stergiou, N., Bates, B. T., & James, S. L. (1999). Asynchrony between subtalar and knee joint function during running. *Medicine and Science in Sports and Exercise*, *31*, 1645–1655.

Trappe, S. (2007). Marathon runners: How do they age? *Sports Medicine*, *37*, 302–305.

van Ingen Schenau, G. J. (1980). Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. *Medicine and Science in Sports and Exercise*, *12*, 257–261.

Wang, J. W., Kuo, K. N., Andriacchi, T. P., & Galante, J. O. (1990). The influence of walking mechanics and time on the results of proximal tibial osteotomy. *Journal of Bone and Joint Surgery, A*, *72*, 905–909.

Young, A., & Dinan, S. (2005). Activity in later life. *British Medical Journal*, *330*, 189–191.