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Flexibility, muscle strength and running biomechanical adaptations in older runners

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ABSTRACT

Background: The increased injury risk in older runners has been associated with alterations in muscle strength, flexibility, and gait biomechanics. This study investigated whether older runners exhibit changes in muscle strength, flexibility and running biomechanics compared to younger runners, and possible relationships between these changes.

Methods: Thirty-five young (20–36 yrs) and 35 older (55–71 yrs) recreational runners participated in the study. Measures of three-dimensional biomechanical data during treadmill running at 2.7 m/s and measures of muscle strength and flexibility were compared between groups. A correlation analysis between biomechanical and clinical variables was also performed.

Findings: Older runners demonstrated an overall reduction in muscle strength and flexibility, and altered running patterns compared to young runners but correlations between clinical and biomechanical variables were scarce. Reduced hip, ankle and trunk excursions along with reduced knee and ankle positive work were found in older runners. Older runners also exhibited increased knee abduction impulse, ankle abduction impulse and vertical loading rates. In contrast, older runners did not present a distal-to-proximal lower extremity joint moment redistribution.

Interpretation: We observed age-related reduced strength and flexibility concomitant with alterations in running biomechanics, but a lack of correlation between these variables. This finding hampers the use of single, or even a subset of characteristics to better understand age-related changes in runners. The observed changes are complex and multivariate in nature. Clinicians will most likely have to monitor both clinical and biomechanical characteristics to optimize care. However, future studies need to prospectively address what are biomechanical age-related risk factors in runners.

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1. Introduction

Over the last decade, a substantial increase in the number of older runners has been observed (Jokl et al., 2004). However, an increased number of running-related injuries among older runners have also been reported (Fields, 2011). The increased injury rate may be partly explained by the changes in musculoskeletal function such as loss in muscle strength (Faulkner et al., 2007) and joint mobility (Nonaka et al., 2002) and also partly explained by the changes in running patterns associated with aging (Bus, 2003; Fukuchi and Duarte, 2008). Although the underlying mechanisms remain unknown, previous studies suggest that age-related changes during walking are caused by musculoskeletal function degeneration (McGibbon, 2003).

Age-related biomechanical alterations during walking have been strongly suggested as a consequence of reduced muscle strength observed in older individuals (McGibbon, 2003). However, the association between reduced muscle force output and changes in kinetics during running in older runners has not been well investigated and has, to date, been limited to the sagittal plane of the ankle and knee joints (Karamanidis and Arampatzis, 2005). One could hypothesize that reduced muscle force output would result in an overall reduced joint work during running.

Loss of range of motion (ROM) with aging (Scott et al., 2007) has been associated with sagittal plane gait changes such as reduced knee and ankle joint angle excursion in older runners (Bus, 2003; Karamanidis and Arampatzis, 2005). However this association has not been consistently observed in the secondary plane of motion. For example, Lilley et al. (2011) reported increased peak knee internal rotation and ankle eversion whereas these findings were not present with other studies (Bus, 2003; Fukuchi and Duarte, 2008). The conflicting literature may be partly explained by a high level of inter-subject variability in secondary plane kinematic data, possibly due to the small

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sample sizes used in these studies. In addition, these previous studies assumed that flexibility is reduced in older runners but did not measure these variables of interest (Bus, 2003; Fukuchi and Duarte, 2008; Karamanidis and Arampatzis, 2005). In light of the limited description of the secondary plane kinematics and the fact that they are linked to running injuries, a description of the lower extremity joint kinematics, along with measures of flexibility in older runners is necessary to determine whether modifiable risk factors can be identified.

Another observed change in the older adults' walking is the joint moment redistribution across lower extremity joints. Specifically, a higher hip joint moment has been reported to possibly compensate for the reduced moments generated by distal joints to produce the same overall support moment (DeVita and Hortobagyi, 2000). However, this distal-to-proximal shift in the moment distribution across the lower extremity joints has only been documented in walking. It is unknown whether this adaptation is also present or amplified during running to help explain the disparate injury occurrence in older runners compared to their younger counterparts, presumably due to increased loading in proximal joints. Previous studies have limited their research to include only running biomechanics of the knee and ankle joints (Fukuchi and Duarte, 2008; Karamanidis and Arampatzis, 2005). It has been shown that trunk movement patterns are influenced by lower extremity joint moments during walking (Nott et al., 2010). Therefore, one can postulate that trunk kinematics would also be affected if a change in the distribution of joint moments occurs during running in older adults. To our knowledge, no study has measured trunk kinematics in older runners.

In summary, considering that muscle weakness and reduced muscle flexibility have been commonly associated with atypical walking biomechanics in older adults, it is likely that a connection between these factors may also be found in running. Despite the evidence suggesting that older runners are more prone to injuries, there is limited understanding on the association between clinical (flexibility and strength) and running biomechanical factors in this population. Therefore, the aim of this study was to investigate differences in muscle strength, flexibility and running gait biomechanical patterns, in a representative sample of young and older runners. We hypothesize that older individuals would exhibit (1) a distal-to-proximal shift in the lower extremity joint moments similarly to walking studies, as measured via angular impulse, to maintain (2) the same overall support moment. In addition, older runners would demonstrate a (3) reduced joint angle excursions concomitant with an (4) overall reduced joint flexibility and a (5) reduced muscle force output compared to their younger counterparts. In addition, we also hypothesize that these biomechanical and clinical variables would be correlated.

2. Methods

2.1. Participants

Thirty-five younger recreational runners (21 males and 14 females) and 35 older runners (22 males and 13 females) were examined in this study. Participants were recruited from local races and posted flyers. Prior to their participation, each subject signed an informed consent form. The demographic information of both groups of subjects can be

Table 1
Mean (SD) subject demographics information of the young and older groups.

	Young	Older	P-value
Demographics			
Age (years)	28.9 (4.7)	60.2 (4.2)	<0.01 ^a
Mass (kg)	67.9 (11.5)	68.4 (11.0)	0.87
Height (cm)	171.7 (8.8)	171.1 (9.6)	0.77
BMI (kg/cm ²)	22.9 (2.4)	23.2 (1.8)	0.54
Weekly training (hours)	3.5 (1.9)	3.2 (0.8)	0.49

^a Indicates significant differences between groups.

found in Table 1. Each participant had to meet the following inclusion criteria: be injury free in the last 3 months; have a weekly running distance of 10–20 km; be familiar with treadmill running (e.g. include treadmill running into their weekly training). In addition, participants were excluded if they presented one or more of the following: lower extremity injury or surgery within the last 3 and 8 months, respectively; head injury or vestibular disorder within the last 6 months. The sample size was determined based on a priori statistical power analysis on the ankle abduction angle at heel strike (Fukuchi and Duarte, 2008). Considering a within-group SD of 3° and expected difference between groups of 2°, a minimum of 34 subjects in each group was required to adequately power the study ($\alpha = 0.05$, $\beta = 0.8$).

2.2. Muscle strength and flexibility measurements

The right leg was used as the test extremity for muscle strength and flexibility measures. Maximal voluntary isometric contraction (MVIC) testing was performed on the following muscle groups: hip abductors (HABDS), hip extensors (HEXTS), knee extensors (KEXTS), ankle plantar-flexors (APFS) and hip external rotators (HERS). Muscle force was measured using a hand-held dynamometer (HHD) (range: 0–1330 N; accuracy: $\pm 1\%$; resolution: 1 N; Nicholas MMT, Lafayette Instruments, Lafayette, USA) and non-elastic adjustable straps. The straps were anchored to the testing bed and the subjects performed each test by pushing into the dynamometer and against the strap. Hence, it was expected that this procedure removed any potential for tester strength or experience to influence the assessment. In all strength measures, the participants were asked to maximally push against the dynamometer by moving the joint toward the instructed direction for 5 s. One practice trial and three experimental trials were performed, with 15 s of rest in between. The mean force (N) of the three MVIC trials was then normalized as a percentage of body weight (%BW).

The hip abductors strength and hip external rotators strength were tested similarly to Snyder et al. (2009). The hip extensors strength test was performed with the subject lying in prone with the right knee in 90° of flexion. The knee extensors strength was tested similarly to Reese (2012) with the participants in a seated position with their hips and knees in 90° of flexion.

Joint (ROM) measures were taken by using either a universal goniometer or a digital inclinometer (Pro 360 digital; SmartTool Technology, Inc., Oklahoma City, OK, USA). The hip adduction ROM and hip extension ROM were tested similarly to those described and illustrated by Ferber et al. (2010). Hip external rotation ROM and hip internal rotation ROM were assessed while the subjects were seated with their hips and knees at 90° while the tester passively moved the lower leg towards the desired direction (Norkin and White, 2003). Ankle dorsiflexion ROM was assessed similarly to Johanson et al. (2008) with the knee both extended and flexed at 90° to better isolate gastrocnemius and soleus muscle flexibility. The hip flexion ROM was measured through a straight leg raise test. The participant's hip was passively moved into flexion while keeping the knee in full extension. An inclinometer was then placed in the anterior aspect of the thigh to quantify the available ROM. A detailed description and illustration of the MVIC and flexibility measures are provided as a supplementary online document (Appendix A). Intra-class correlation coefficient (ICC 2,1) was calculated to determine intra-tester reliability for flexibility and strength measures for five volunteers prior to the commencement of the study.

2.3. Biomechanical measures

Biomechanical data were collected using an eight-camera system (MX3, Vicon Motion Systems, Oxford, UK). A combination of anatomical and technical markers was used as illustrated in Fig. 1. This kinematic gait model has displayed good reliability and a detailed description of the model can be found in a previous study (Pohl et al., 2010).

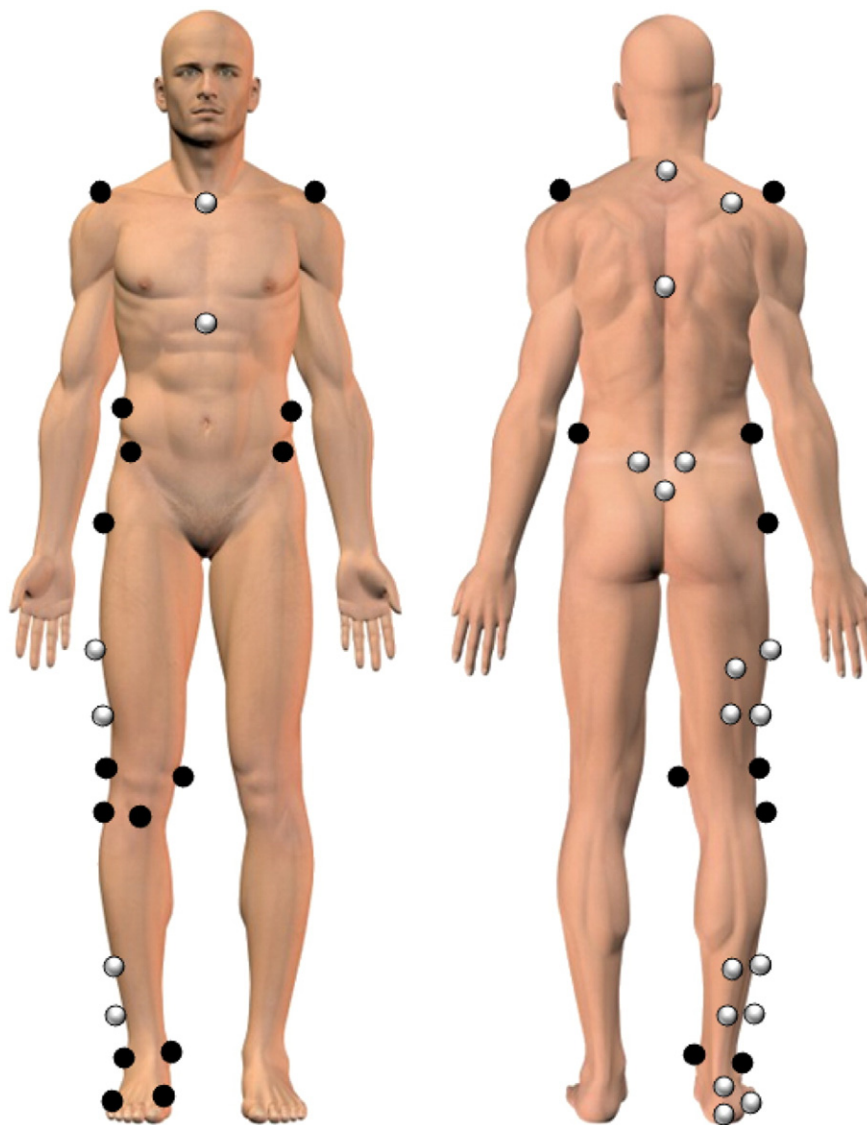


Fig. 1. Marker set protocol used in this study depicting anatomical (black) and technical (white) markers used in the study.

Following a standing calibration trial, the anatomical markers were removed and the subjects ran on an instrumented treadmill (Bertec, Columbus, OH, USA) at 2.7 m/s after a 3 minute accommodation period. All participants wore standard, neutral shoes (Nike Air Pegasus, Nike, Portland, OR, USA). The kinematic data and the ground reaction force (GRF) data were collected at 200 Hz and 1000 Hz, respectively. The heel strike and toe off were determined when the vertical GRF crossed a 40 N threshold level. Raw marker trajectory data and GRF data were filtered using a fourth order low-pass Butterworth filter with cut-off frequencies of 10 Hz and 50 Hz, respectively. Three-dimensional hip, knee, and ankle angles were calculated using cardan angles with the distal segment expressed relative to the proximal segment. The net internal joint moments and joint powers were calculated using a standard inverse dynamics approach. Joint impulse and joint work were computed as the area under the moment-time and power-time curves, respectively. The joint kinetic and the GRF variables were normalized by subject's body mass.

Visual 3D software (C-motion Inc., Germantown, MD, USA) was used to filter the marker and GRF data and to calculate joint kinematics and kinetics. Joint angles, joint moments and powers were normalized to the stance phase over 101 data points. Individual and group mean parameters were obtained using in-house algorithms developed in Matlab 7.12 (Mathworks Inc., Natick, MA, USA). The average time-

distance parameters and average plots of kinematic and kinetic parameters were obtained from 10 footfalls. For a better characterization of the older runners' gait pattern, we selected variables commonly reported previously (Bus, 2003; Fukuchi and Duarte, 2008; Karamanidis and Arampatzis, 2005; Lilley et al., 2011). Excursion angles (difference between maximal and minimal values) were obtained for all joints in all three planes of motion. The maximal loading rate, the magnitude of the impact peak and the active peak of the vertical GRF, and the magnitude of the braking and propulsion peaks of the horizontal GRF were also quantified.

2.4. Data analysis

Descriptive statistics (mean and SD) were calculated for all biomechanical, strength and flexibility variables for both groups of young and older runners. The normality of the data was verified by the Lilliefors test. When the normality assumption was not met non-parametric statistics were used. Independent samples t-tests or Wilcoxon signed rank sum tests were carried out to detect differences between-groups and statistical analysis was performed in Matlab 7.12 (Mathworks Inc., Natick, MA). The mean ensemble time-series of joint angle, joint moment, joint power and GRF curves across participants in each group were calculated to illustrate the overall group pattern. Pearson

or Kendall's tau correlation analysis was employed on selected variables to assess the relation between some clinical and biomechanical factors. The Cohen's *d* effect size of each variable was also quantified. The significance level for all statistical analyses was set at $\alpha = 0.05$.

3. Results

The young and older runners were all comparable in terms of height, mass, BMI and weekly training hours (Table 1).

Detailed results of the strength and flexibility measures are provided in Table 2. Older runners exhibited significantly reduced hip adduction ROM, ankle gastrocnemius ROM, ankle soleus ROM, hip internal rotation ROM and hip external rotation ROM whereas hip extension ROM and hip flexion ROM were similar between groups. In addition, the older runners demonstrated significantly reduced strength in the hip abductors, hip extensors and ankle plantar flexors whereas no differences were found for hip external rotators and hip extensors when compared to the younger runners (Table 2).

Ensemble means ($\pm 1SD$) group joint kinematics (Fig. 2) and joint kinetics (Fig. 3) are presented. Older runners exhibited significantly reduced ankle dorsiflexion–plantarflexion and hip adduction–abduction. Older runners also demonstrated significantly reduced Thorax/Pelvis (Tho/Pel) extension–flexion and Tho/Pel internal rotation–external rotation as demonstrated in Table 3.

Detailed results of the joint kinetics and GRF variables are presented in Table 3. Joint moment impulses in the sagittal plane were similar between groups followed by a similar support moment impulse between groups. However, increased knee ABD, knee ER, and ankle ABD impulses; and increased maximal loading rate were observed in older runners. Conversely, older runners presented decreased ankle INV impulse; knee and ankle positive work; and reduced GRF propulsion and active vertical GRF values.

Effect sizes were generally larger for the clinical variables (flexibility and strength) (Table 2) compared to the biomechanical measures (Table 3). The ICC (2,1) ranged from 0.60 to 0.87 and from 0.71 to 0.96 for the flexibility and strength measures, respectively; thus indicating good to excellent reliability in the clinical measurements (Shrout and Fleiss, 1979).

In regard to the correlation analysis, there were significant correlations across participants for ankle plantar flexors strength and ankle positive work ($r = 0.23, P < 0.01$); ankle plantar flexors strength and GRF propulsion peak ($r = 0.18, P = 0.03$); and ankle plantar flexors strength and vertical active GRF peak ($r = 0.25, P < 0.01$). In contrast, there was no significant correlation across participants for ankle gastrocnemius ROM and ankle DF–PF excursion ($r = -0.04, P = 0.72$);

ankle soleus ROM and ankle DF–PF excursion ($r = 0.02, P = 0.80$); hip adduction ROM and hip ADD–ABD ($r = -0.02, P = 0.84$) and hip abductors strength and knee ABD impulse ($r = -0.10, P = 0.22$).

4. Discussion

The aim of this study was to examine the differences in flexibility, muscle strength and running biomechanics between younger and older runners. This is an important area of investigation considering the limited research related to understanding the inter-relationship between sarcopenia and the greater incidence of injury for older runners. Although cause and effect relationships between these factors have not yet been established, previous studies suggest that age-related gait changes are caused by musculoskeletal function degeneration (McGibbon, 2003).

Although, the older runners exhibited reduced MVIC as compared to younger runners, these differences were not consistently reflected in the joint work during running. In fact, there was a significant correlation between MVIC and the corresponding joint work for the ankle but not for the hip and knee joints. The lack of correspondence between MVIC and joint kinetics has previously been observed in older runners (Karamanidis and Arampatzis, 2005). However, these relationships have not been investigated in the hip joint and in other planes of motion. An explanation could be that biological aging affects the contraction velocity to a greater extent as compared to the MVIC that was measured in the present study. An alternative explanation may be related to the specific way the MVIC was measured. While the position of the participants allowed good reliability in comparison with previous studies, the specific limb position may not represent the functional demands placed on the muscles during running. Nevertheless, the results of this study suggest that the weakness in distal muscles (e.g. calf muscles) compared to the proximal muscles affected, to a greater extent, the gait pattern in older runners.

In support of our hypotheses, older runners exhibited significantly reduced ankle flexibility and reduced ankle DF–PF during running compared to their young counterparts. However, no correlation was found between these variables and could be explained by the fact that running does not require substantial joint mobility relative to the available passive joint ROM. In fact, there is conflicting evidence on whether ankle DF–PF is affected by aging during running with some evidence of reduction (Bus, 2003) whereas others show similar patterns (Fukuchi and Duarte, 2008). In addition, the older runners in the current study exhibited increased tightness in the iliotibial band (ITB) and reduced hip ADD–ABD, but no correlation was found between them, indicating that other structures may be responsible to restrict hip joint mobility in older runners. Irrespective of their cause, reduced sagittal ankle ROM and hip frontal ROM, both static and dynamic, have been previously associated with injuries such as ITB syndrome, patellar tendinitis and plantar fasciitis (Grau et al., 2011; Hudson and Darthuy, 2009; Malliaras et al., 2006; Wearing et al., 2006). Hence, it is reasonable to conclude that older runners may be at higher risk to sustain an injury.

A distal-to-proximal shift in joint moments has been previously documented in walking studies (DeVita and Hortobagyi, 2000; Savelberg et al., 2007). We hypothesized that such a shift should also occur during running and considering the higher demand running places on the skeletal muscles, we expected a similar or greater shift than during walking. Our results do not support this hypothesis as the older adults displayed similar joint moment impulse patterns as compared to the younger group. In fact, the joint moment impulse distribution across hip, knee and ankle joints were similar between groups, highlighting that the same strategy was adopted which was confirmed by the similar support moment impulses during running. It is possible that the increased demand of running does not require a distal-to-proximal shift in the joint moments for this particular group of older runners since they were generally more active compared to the ones assessed in previous walking studies. Alternatively, the participants in the present study

Table 2
Mean (SD) ROM and MVIC variables of interest for young and older runners, along with *P*-values and effect sizes.

Variables	Young	Older	<i>P</i> -value	Effect size
<i>Flexibility</i>				
Hip extension (°)	−16.4 (7.51)	−16.78 (9.63)	0.84	0.05
Hip adduction (°)	−32.86 (5.71)	−27.10 (2.97)	<0.01 ^a	1.28
Hip flexion (°)	81.15 (9.48)	77.56 (12.63)	0.18	0.33
Ankle gastrocnemius (°)	94.23 (5.79)	88.31 (4.57)	<0.01 ^a	1.15
Ankle soleus (°)	105.00 (6.81)	96.03 (3.93)	<0.01 ^a	1.64
Hip external rotation (°)	42.49 (7.35)	35.26 (5.62)	<0.01 ^a	1.12
Hip internal rotation (°)	45.00 (7.29)	37.57 (8.05)	<0.01 ^a	0.98
<i>Strength</i>				
Hip abductors (%BW)	0.35 (0.07)	0.30 (0.06)	<0.01 ^a	0.65
Hip extensors (%BW)	0.28 (0.08)	0.23 (0.05)	<0.01 ^a	0.78
Ankle plantar flexors (%BW)	0.56 (0.12)	0.38 (0.07)	<0.01 ^a	1.90
Hip internal rotators (%BW)	0.20 (0.05)	0.18 (0.05)	0.21	0.31
Hip external rotators (%BW)	0.17 (0.04)	0.16 (0.04)	0.09	0.41
Knee extensors (%BW)	0.45 (0.08)	0.43 (0.11)	0.48	0.17

^a Indicates significant differences between groups.

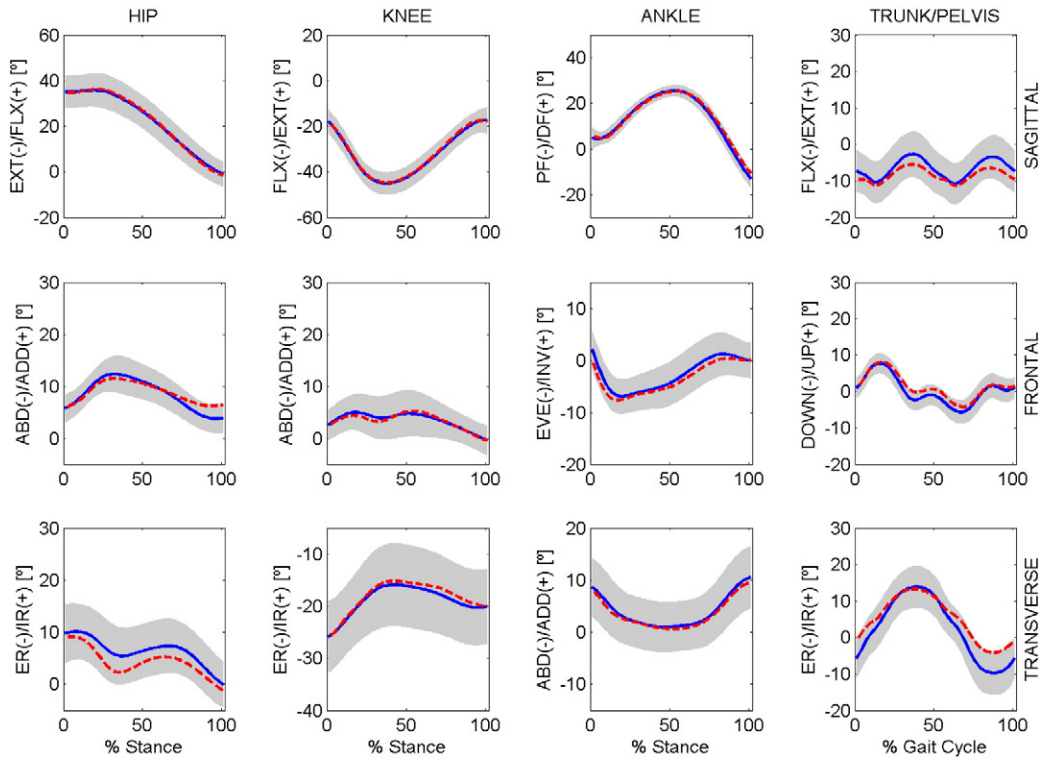


Fig. 2. Three-dimensional hip, knee, ankle and trunk/pelvis joint kinematics for young (solid blue line is mean, shaded area is $\pm 1SD$) and older (dashed red line is mean) runners. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

were well matched in terms of demographics and training levels as opposed to previous studies where the participants in the older group were generally shorter and less active than their young counterparts (DeVita and Hortobagyi, 2000; Savelberg et al., 2007). Hence, this fact

may explain the absence of differences in joint moment distribution. The lack of studies investigating the lower extremity joint moment distribution in older runners during running prevented any further comparison.

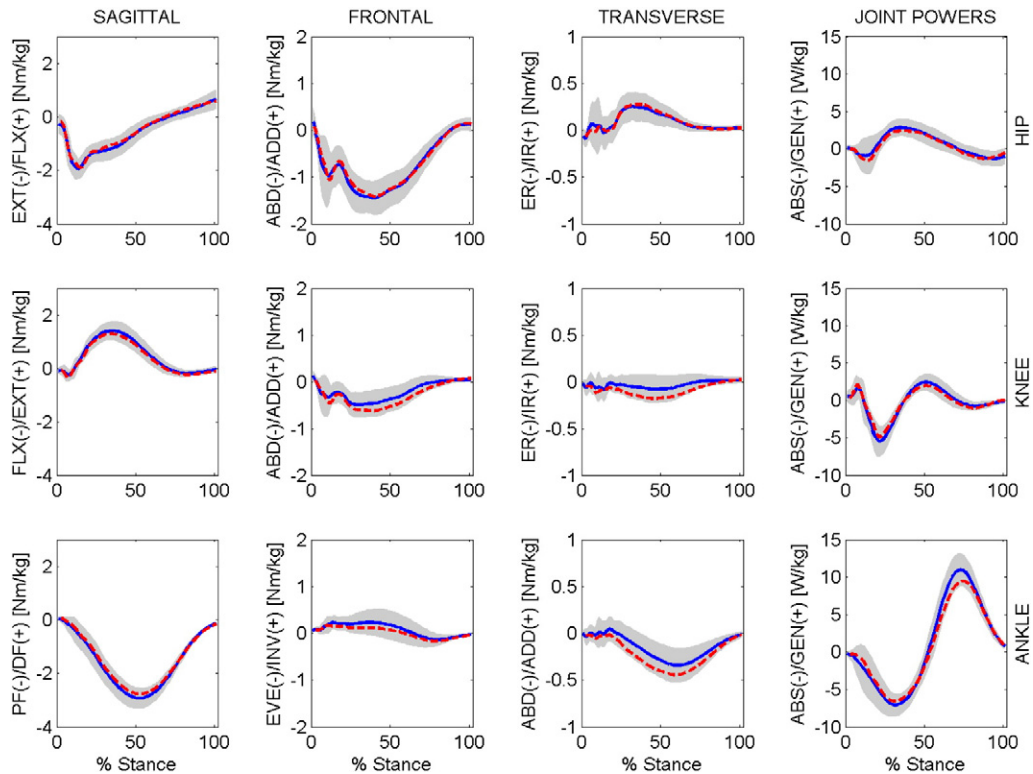


Fig. 3. Three-dimensional hip, knee and ankle joint moments; and sagittal power for young (solid blue line is mean, shaded area is $\pm 1SD$) and older (dashed red line is mean) runners during the stance phase of running. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Mean (SD) joint kinematic, joint kinetic and GRF variables of interest for young and older runners, along with *P*-values and effect sizes.

Variables	Young	Older	<i>P</i> -value	Effect size
<i>Excursion angle</i>				
Hip FLX–EXT (°)	38.0 (4.9)	38.94 (3.72)	0.35	0.23
Hip ADD–ABD (°)	10.66 (3.15)	8.38 (3.27)	<0.01 ^a	0.72
Hip IR–ER (°)	3.64 (1.05)	3.74 (1.25)	0.71	0.09
Knee EXT–FLX (°)	31.53 (4.81)	29.40 (4.64)	0.06	0.46
Knee ADD–ABD (°)	7.00 (2.68)	7.04 (2.29)	0.95	0.02
Knee IR–ER (°)	11.72 (2.92)	12.57 (3.47)	0.27	0.27
Ankle DF–PF (°)	38.85 (3.67)	35.94 (4.37)	<0.01 ^a	0.73
Ankle INV–EV (°)	11.00 (2.02)	10.22 (2.99)	0.20	0.31
Ankle ADD–ABD (°)	11.13 (2.84)	10.90 (2.81)	0.73	0.08
Tho/Pel EXT–FLX (°)	10.72 (2.94)	9.12 (2.75)	0.02 ^a	0.57
Tho/Pel IPSI–CONTRA (°)	14.22 (2.79)	13.51 (3.56)	0.36	0.23
Tho/Pel IR–ER (°)	24.99 (6.58)	19.60 (5.48)	<0.01 ^a	0.90
<i>Angular impulse</i>				
Hip EXT (Nms/kg)	−0.7 (0.2)	−0.72 (0.34)	0.61	0.13
Hip ABD (Nms/kg)	−0.78 (0.23)	−0.77 (0.29)	0.78	0.07
Hip ER (Nms/kg)	0.11 (0.06)	0.11 (0.06)	0.87	0.04
Knee EXT (Nms/kg)	0.51 (0.16)	0.46 (0.20)	0.26	0.28
Knee ABD (Nms/kg)	−0.25 (0.14)	−0.33 (0.15)	0.03 ^a	0.54
Knee ER (Nms/kg)	−0.06 (0.05)	−0.10 (0.07)	<0.01 ^a	0.65
Ankle PF (Nms/kg)	−1.56 (0.28)	−1.46 (0.26)	0.15	0.35
Ankle INV (Nms/kg)	0.14 (0.11)	0.08 (0.06)	<0.01 ^a	0.65
Ankle EV (Nms/kg)	−0.06 (0.08)	−0.07 (0.06)	0.83	0.05
Ankle ABD (Nms/kg)	−0.17 (0.10)	−0.23 (0.09)	0.02 ^a	0.58
Support moment (Nms/kg)	2.59 (0.40)	2.38 (0.47)	0.06	0.48
<i>Joint work</i>				
Hip positive work (J/kg)	1.08 (0.57)	0.98 (0.69)	0.54	0.15
Hip negative work (J/kg)	−0.61 (0.33)	−0.70 (0.45)	0.32	0.24
Knee positive work (J/kg)	0.77 (0.27)	0.63 (0.28)	0.04 ^a	0.52
Knee negative work (J/kg)	−1.15 (0.39)	−0.96 (0.43)	0.07	0.45
Ankle positive work (J/kg)	3.13 (0.72)	2.70 (0.58)	<0.01 ^a	0.66
Ankle negative work (J/kg)	−2.16 (0.64)	−1.93 (0.58)	0.12	0.39
<i>GRF</i>				
Braking peak (N/kg)	−0.27 (0.05)	−0.26 (0.04)	0.25	0.28
Propulsion peak (N/kg)	0.21 (0.03)	0.19 (0.03)	0.03 ^a	0.53
Impact peak (N/kg)	1.54 (0.22)	1.62 (0.21)	0.22	0.35
Vertical active peak (N/kg)	2.35 (0.21)	2.22 (0.26)	0.03 ^a	0.55
Maximal loading rate (BW/s)	36.11 (11.52)	42.67 (9.57)	0.03 ^a	0.63

EXT = extension, FLX = flexion, ADD = adduction, ABD = abduction, IR = internal rotation, ER = external rotation, DF = dorsiflexion, PF = plantarflexion, INV = inversion, EV = eversion. Tho/Pel = joint angle between thorax and pelvic segments. For the Tho/Pel joint: trunk bending towards posterior (EXT) and anterior (FLX) side of the body, trunk bending to the right (IPSI) and left (CONTRA) side, trunk axial rotation to the right (ER) side and left (IR).

^a Indicates significant differences between groups.

The older runners in the present study exhibited a higher knee ABD impulse along with reduced HABDS as compared to the younger runners, although no correlation was found between these variables. The lack of correlation between these variables could be explained by the nature of the variables selected for analysis. While muscle strength was measured isometrically and represented a static measure, the knee ABD impulse consisted of the cumulative twisting load during the stance phase of running. Earl and Hoch (2011) also found reduced knee ABD moment and increased HABDS following an exercise program in runners with patellofemoral pain syndrome (PFPS). However, no correlation analysis was performed to assess the relationship between these variables. An increased frontal plane moment has also been documented in mature runners (Lilley et al., 2011) and it has been considered a predictor of both PFPS (Stefanyshyn et al., 2006) and knee OA progression (Miyazaki et al., 2002). In addition, reduced HABDS has been identified in PFPS runners when compared to controls (Dierks et al., 2008). Hence, although previous studies suggest that knee frontal plane loading may be modified through hip abductor strengthening exercises, the underlying mechanism needs to be further explored.

In the present study, an increased knee ER impulse and greater ankle ABD impulse were found in older runners. The increased knee ER moment has also been documented in individuals presenting moderate knee OA (Astefhen et al., 2008). Regardless of their cause, the changes in secondary plane mechanics at the knee can accelerate the progression of degenerative changes by placing new loads on regions of the articular cartilage that were previously conditioned for different load levels.

The older runners exhibited reduced vertical GRF active peak and horizontal GRF propulsion peak compared to the young runners and these results are similar to previous studies (Bus, 2003; Karamanidis and Arampatzis, 2005). The reduced MVIC, particularly in the calf musculature, may have contributed to these findings. In fact, there was a significant correlation between APFS and both GRF horizontal propulsion and GRF vertical active peak. An increased maximal loading rate of the vertical GRF was displayed by older runners, thus suggesting that they have poor shock absorption capabilities. Indeed, this finding has been consistently documented in previous studies that examined older runners' gait patterns (Bus, 2003; Lilley et al., 2011). Although not fully understood, high loading rates have been associated with injuries in younger runners (Zadpoor and Nikooyan, 2011) who presumably have enhanced tissue shock absorption capabilities compared to older runners. Hence, higher tissue strain rates as a result of the increased loading rates combined with reduced shock attenuation capabilities, reported previously in older adults (Hsu et al., 1998), may increase the injury risk of older runners.

An overall reduction in the trunk excursion was observed in older runners, particularly in Tho/Pel EXT–FLX and Tho/Pel IR–ER (Fig. 2). Previous studies have observed reduced ROM, particularly in the lumbar spine with age (McGill et al., 1999). However, the lack of studies examining the trunk movements in older runners prevents any comparison with the literature. We speculate that the increased stiffness in the trunk and spine structures, although not directly measured, may have also negatively influenced trunk mobility during running and may contribute to musculoskeletal injury such as low back pain (Mellin, 1990).

There were some limitations in this study that need to be highlighted. The presence of multiple dependent variables with the inclusion of clinical and biomechanical measures may have increased the chance of type I error. However, as the numbers of significant differences and significant correlations were limited relative to the number of dependent variables, it is unlikely that this was an issue in the present study. Although, the sample size was the largest ever recorded in studies on running biomechanics in older individuals, it was possible that the study was underpowered, particularly for the correlation analysis. Nonetheless, the conclusions were likely not affected considering the lack of correlation between clinical and biomechanical variables. Lastly, we acknowledge that more objective and direct clinical measures could be adopted to better understand the underlying mechanisms of biological aging on running biomechanical patterns. We chose simple clinical measures since they have been widely used by clinicians to quantify both muscle strength and flexibility and therefore the external validity of the results could be enhanced. Nonetheless, future studies need to be conducted to address the effects of biological aging on running biomechanics before intervention studies can be designed to prevent running-related injuries in this growing population.

5. Conclusion

Overall, the results of the present study provide further evidence that biological aging results in reduced muscle force output, reduced joint flexibility, and alterations in running biomechanics. Specifically, older runners exhibited reduced hip, ankle and trunk kinematic excursions, reduced knee and ankle positive work as well as increased knee abduction impulse and vertical loading rates as compared to their younger counterparts. This study also measured a poor relationship between clinical and running biomechanical variables indicating that the age-related biomechanical and clinical changes are complex and

multivariate in nature. Clinicians should monitor both clinical and biomechanical characteristics to optimize care and future research studies need to prospectively monitor which biomechanical age-related risk factors are related to running injuries and whether they can be modified.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.clinbiomech.2013.12.007>.

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