Changes in Vertical and Joint Stiffness in Runners With Advancing Age

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Abstract

Powell, DW and Williams, DSB. Changes in vertical and joint stiffness in runners with advancing age. J Strength Cond Res 32 (12): 3425–3431, 2018—Age-related changes in the neuromuscular system underlie reduced performance and injury but may be mitigated through regular physical activity. It was hypothesized that older (OLD) compared with young (YOUNG) adults would exhibit greater vertical and joint stiffness when running at 3.35 m·s⁻¹. Nine YOUNG and 10 OLD runners performed over ground running trials while three-dimensional biomechanics were recorded. Ankle and knee joint angles, moments and stiffness values were compared between YOUNG & OLD. YOUNG had smaller vertical stiffness (p = 0.01; YOUNG: 32.8 ± 3.6; OLD: 38.1 ± 5.7) and greater joint stiffness than OLD at the ankle (p = 0.04; YOUNG: 0.134 ± 0.021; OLD: 0.118 ± 0.017) and knee (p = 0.01; YOUNG: 0.119 ± 0.016; OLD: 0.098 ± 0.014). YOUNG exhibited greater peak knee flexion angles (p = 0.04; YOUNG: 43.4 ± 6.5°; OLD: 39.1 ± 2.6°), and peak ankle plantarflexion (p = 0.02; YOUNG: −2.8 ± 0.4 Nm·kg⁻¹; OLD: −2.5 ± 0.1 Nm·kg⁻¹) and knee extension moments (p < 0.01; 2.6 ± 0.3 Nm·kg⁻¹; OLD: 2.1 ± 0.2 Nm·kg⁻¹) than OLD whereas no differences were observed in peak ankle dorsiflexion angles (p = 0.44; YOUNG: 23.6 ± 4.2°; OLD: 23.4 ± 2.1°). The findings of this study suggest that OLD compared with YOUNG adults adopt altered lower extremity biomechanics. These altered running biomechanics by seek to minimize the metabolic cost of running or may be a function of reduced lower extremity strength and power.

Keywords: aging, running, kinetics, moments, biomechanics

Introduction

Remaining physically active throughout the lifespan has been shown to ameliorate declines in neuromuscular, skeletal, and cardiovascular health (21–23,25,26,30). Running is a common form of physical activity that is relatively inexpensive, easily accessible to most individuals and has been shown to reduce age-related declines in neuromuscular and cardiovascular performance, and skeletal health (21–23,30). Though running has been shown to provide health benefits with advancing age, it is also associated with significant rates of injury (24).

Research has shown that a vast majority of runners will experience a significant musculoskeletal injury requiring cessation from training for a period of at least 1 week (12). This rate of injury may be substantially greater in the presence of excessive stiffness or lower extremity malalignment (20,33). Data have shown that middle-aged and older runners (>45 years) exhibit a greater propensity for musculoskeletal injuries compared with their younger counterparts (24,25). Specifically, middle-aged and older runners experience injuries to the soft tissues of the posterior aspect of the lower extremity including the Achilles-Gastrocnemius complex and the knee flexors (24). The unique injury patterns experienced by older adults are, in part, the result of changes in the physiological properties of the musculotendinous tissues (18) along with altered running biomechanics (6).

Though remaining physically active has been shown to reduce immobility and disability with advancing age (10,31), age-related changes in the mechanical properties of musculotendinous tissues (MTUs) remain. Research has demonstrated that muscle strength (29) and tendon stiffness (18) are significantly reduced beyond the fifth decade of life suggesting that these tissues may be at greater risk of significant injury in older athletes. However, a limitation of these studies into MTU quality has focused on passive or single-joint movements rather than a multijoint tasks such as walking or running which incorporate not only the mechanical properties of the tissue, but also the active neuromuscular components during the locomotion-based movement. The outcome of the interaction of active neuromuscular strategy with age-related changes in the mechanical properties of the MTU may be evidenced by altered kinematic and kinetic profiles with advancing age. Previous research has demonstrated that older runners adopt unique running biomechanics compared with young runners including slower running velocities, shorter steps, and reduced ankle torques and powers (3,6,11). A better understanding of the interaction of mechanical tissue properties and neuromuscular strategy would provide insight into human performance and injury patterns with advancing age.
One variable that has been shown to be associated with both running performance and injury is stiffness (1,4). Stiffness is a composite measure of kinematics and kinetics that describes the interaction of load placed on a structure and the structure’s response to that load (4,8,27,28). As it pertains to the human system, stiffness has been described using a variety of measures including vertical stiffness, leg stiffness, and torsional stiffness (4,8,9,27,28). Accumulating evidence suggests that stiffness may be an underlying factor in injury mechanisms. For example, high-compared with low-arched athletes exhibit significantly greater joint and vertical stiffness in running and landing, respectively (27,28,32). As such, high-arched athletes exhibit a greater propensity for bony injuries to the lateral aspect of the lower extremity, whereas low-arched athletes exhibit greater rates of soft tissue injuries to the medial aspect of the lower extremity (33). Moreover, Granata et al. (13) revealed that female athletes have significantly smaller knee joint stiffness values compared with male athletes during landing tasks and suggested that insufficient knee joint stiffness may be a contributing factor to the disproportionate rate of knee ligament injuries in female athletes. Though the relationship between stiffness and lower extremity injury has not been well established, it has been suggested that insufficient or excessive stiffness within the lower extremity places individuals at an exaggerated risk of injury (4,32,34).

Although evidence suggests that stiffness within the lower extremity is a contributor to lower extremity injury during athletic tasks including running and landing, little evidence is available regarding the effect of advancing age on stiffness within the lower extremity during running. Therefore, the purpose of this study was to compare vertical and joint stiffness values and their underlying components in healthy younger and healthy older adults during an over ground running task. We hypothesized that older adults would exhibit greater vertical stiffness values and significantly greater ankle and knee dynamic joint stiffness values.

**METHODS**

Experimental Approach to the Problem

Each participant performed 24 successful level running trials across a 20-meter runway at a fixed velocity (3.35 m $\cdot$ s$^{-1}$) in neutral laboratory running shoes. A successful trial was characterized by the participant running across the 20-meter runway at the selected velocity ($\pm 5\%$) and the participant’s foot being completely supported by the embedded force platform, whereas initial contact was made with a heel strike. Though strike pattern was not controlled in this study and no instructions were provided regarding running mechanics, all participants performed running trials with a heel strike as indicated by foot strike angle. A trial was considered unsuccessful and repeated if each of these criteria were not met. Testing of right and left lower extremities was randomized using a random number generator. Participants were provided a minimum rest period of 30 seconds between trials to prevent fatigue. If requested, participants were allotted more time between trials. No participants requested additional time or reported fatigue during the testing protocol.

**Subjects**

Nine healthy young adults (YOUNG) and 10 healthy older adults (OLD) participated in this study. Individuals in the YOUNG group were aged between 30 and 40 years whereas individuals in the OLD group were aged between 60 and 70 years. All participants were regularly active runners and reported running at least 30 minutes most days of the week ($\geq 4$ days). Participants were excluded from the study if they had a current or recent history (within 6 weeks) of lower extremity injury or a history of major lower extremity surgery (i.e., total joint arthroplasty). The study protocol was approved by the Virginia Commonwealth University.
Institutional Review Board and all participants provided written informed consent before participation in this study.

**Procedures**

**Instrumentation.** A 9-camera motion analysis system (240 Hz, Ocus 3; Qualisys, Inc., Goteborg, Sweden) and five 60 × 60 cm force platforms (960 Hz, OR-7; AMTI, Inc., Natick, MA, USA) were used to collect three-dimensional kinematics and ground reaction forces, respectively, from the right and left lower extremities of each participant. Retroreflective markers were placed over anatomical landmarks including the first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, and left and right greater trochanters. The pelvis was defined using single retroreflective markers placed on the right and left anterior superior iliac spines and the L5S1 junction. The pelvis was tracked using these same 3 markers. Retroreflective markers placed on rigid clusters were used to track the thigh and shank. The rearfoot was tracked using 3 single retroreflective markers placed on the participant's shoe over the superior and inferior posterior calcaneus and the lateral aspect of the calcaneus at the peroneal tubercle. After a standing calibration trial, all anatomical markers were removed, leaving only tracking markers on the pelvis, thigh, shank, and rearfoot.

**Data Analysis.** Kinematics and kinetics were analyzed from initial contact to toe off. Initial contact was defined as the time at which the vertical ground reaction force (VGRF) exceeded 20 N for a period of at least 0.03 seconds, whereas toe off was defined as the point after initial contact at which the VGRF fell below 20 N for a period of at least 0.3 seconds. All original marker data and ground reaction force data were filtered using a fourth order zero-lag Butterworth lowpass filter with a 12 Hz cutoff frequency. Three-dimensional ankle and knee joint angles and internal joint moments (14) were calculated using Visual 3D (C-Motion, Inc., Germantown, MD, USA) using an X-Y-Z Cardan sequence. The ankle joint angle was defined as the difference between the angle of the shank and the angle of the foot minus 90°, to account for the orientation of the foot. For example, during quiet standing, the ankle joint angle would be 0° as the longitudinal axis of the foot is perpendicular (in the sagittal plane) to the longitudinal axis of the shank. Internal joint moments were normalized to body mass.

Custom software (Matlab 2013a; MathWorks, Natick, MA, USA) was used to calculate discrete kinematic and kinetic variables of interest for the ankle and knee including peak joint angles, joint excursions, joint moments, dynamic joint stiffness, and vertical stiffness. Dynamic joint stiffness (Figure 1) was calculated as the slope of the angle-moment plot during the braking portion of the stance phase (28). Vertical stiffness was calculated as the peak vertical ground reaction force divided by the vertical displacement of the pelvis (L5S1 marker) between initial contact and peak

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**Table 1.** Mean age and anthropometric measurements of YOUNG and OLD runners.*†

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yr)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YOUNG</td>
<td>33.6 ± 5.2</td>
<td>1.82 ± 0.09</td>
<td>75.7 ± 6.9</td>
</tr>
<tr>
<td>OLD</td>
<td>63.6 ± 3.6</td>
<td>1.78 ± 0.06</td>
<td>74.2 ± 7.4</td>
</tr>
<tr>
<td>p-value</td>
<td>0.150</td>
<td>0.322</td>
<td></td>
</tr>
</tbody>
</table>

*Results of statistical comparisons are also presented (p-value). Presented as mean (SD).
†Statistically significant differences are indicated by p-values less than 0.05.
vertical ground reaction force. Because of its speed-sensitive nature, vertical stiffness was selected to represent lower extremity function (2). Subject means were calculated as the average of the 12 trials from each individual limb.

**Statistical Analyses**

A Shapiro-Wilk test was conducted to assess data for normality. Independent samples t tests were used to compare discrete kinematic and kinetic variables from the left and right limbs for each variable of interest. As no significant differences were observed between the left and right sides for YOUNG or OLD groups, left and right sides were combined. All statistical analyses were conducted on the collapsed data. Univariate analyses of variance were used to compare discrete kinematic and kinetic variables in YOUNG versus OLD adults including peak ankle and knee joint angles and moments, ankle and knee dynamic joint stiffness, and vertical stiffness. Cohen’s d was used to quantify effect size magnitude (5). Significance was set at $p \leq 0.05$. All statistical analyses were conducted using SPSS 21.0 (IBM, Chicago, IL, USA).

**RESULTS**

YOUNG and OLD runners had similar heights (Table 1). The Shapiro-Wilk test revealed that stiffness data were normally distributed ($k_{\text{Ankle}}: p = 0.653$; $k_{\text{Knee}}: p = 0.489$; $k_{\text{Vertical}}: p = 0.634$). YOUNG runners exhibited smaller vertical stiffness values compared with OLD runners ($p = 0.01; d = 1.12$, Figure 2). Dynamic joint stiffness (Figure 3) was greater in YOUNG compared with OLD runners at the ankle ($p = 0.04, d = 0.84$) and knee ($p = 0.01, d = 1.40$). A small but nonsignificant difference ($p = 0.019, d = 0.38$) in peak vertical ground reaction forces were observed between YOUNG and OLD runners (YOUNG: 2.54 ± 0.18 BW; OLD: 2.47 ± 0.19 BW). OLD runners exhibited smaller vertical pelvic excursions compared with YOUNG runners ($p = 0.01; d = 1.10$) as tracked by the L5S1 marker (YOUNG: 0.076 ± 0.010 m; OLD: 0.066 ± 0.009 m).
Age-Related Stiffness in Running

**Table 2.** Mean values for ankle and knee joint kinematics and kinetics including peak ankle dorsiflexion (DF) angle, ankle dorsiflexion excursion, peak ankle plantarflexion (PF) moment, peak knee flexion angle, knee flexion excursion, and peak knee extension moment.*†

<table>
<thead>
<tr>
<th>Group</th>
<th>Ankle DF angle (degrees)</th>
<th>Ankle DF excursion (degrees)</th>
<th>Ankle PF moment (N·m·kg⁻¹)</th>
<th>Knee flexion angle (degrees)</th>
<th>Knee flexion excursion (degrees)</th>
<th>Knee extension moment (N·m·kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YOUNG</td>
<td>23.6 (4.2)</td>
<td>16.6 (4.3)</td>
<td>−2.83 (0.35)</td>
<td>43.4 (6.5)</td>
<td>33.1 (8.7)</td>
<td>2.66 (0.25)</td>
</tr>
<tr>
<td>OLD</td>
<td>23.4 (2.1)</td>
<td>12.6 (3.3)</td>
<td>−2.56 (0.11)</td>
<td>39.1 (2.7)</td>
<td>26.3 (5.0)</td>
<td>2.13 (0.24)</td>
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<tr>
<td>p-value</td>
<td>0.44</td>
<td>0.02</td>
<td>0.04</td>
<td>0.041</td>
<td>&lt;0.01</td>
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</tbody>
</table>

*Results of statistical assessments are also presented (p-value). Presented as mean (SD).†Statistically significant differences are indicated by p-values less than 0.05.

Figures 4 and 5 present joint angle (A) and joint moment (B) data from representative YOUNG and OLD subjects for the ankle and knee, respectively. No differences were observed in peak dorsiflexion angles between the YOUNG and OLD runners (p = 0.44, d = 0.07, Table 2); however, OLD runners exhibited significantly smaller ankle dorsiflexion excursion than YOUNG runners (p = 0.02). YOUNG runners produced greater peak ankle plantarflexion moments compared with OLD adults (p = 0.02, d = 1.04, Table 2). YOUNG runners also exhibited greater peak knee joint flexion angles (p = 0.04, d = 0.88, Table 2) and knee flexion excursions compared with OLD runners (p = 0.041). Furthermore, YOUNG runners had greater peak knee extension moments compared with OLD runners (p < 0.01, d = 2.16, Table 2).

**DISCUSSION**

The purpose of this study was to investigate the effects of advancing age on vertical and lower extremity dynamic joint stiffness. The current data demonstrate that older runners exhibit greater vertical stiffness, but smaller dynamic joint stiffness at the ankle and knee compared to young runners. These data also revealed that older runners produced significantly smaller ankle plantarflexion and knee extension moments while exhibiting smaller peak knee flexion angles compared with young runners. Overall, these findings suggest that advancing age is associated with altered lower extremity joint kinematics and kinetics during running culminating in divergent vertical and joint stiffness findings.

Existing literature has investigated age-related changes in lower extremity biomechanics during locomotor tasks including running (6,11,15–19). However, no previous research has directly investigated the effects of age-related differences in either vertical stiffness or dynamic joint stiffness during running locomotion. The findings of this study support the hypothesis that older adults exhibit greater vertical stiffness compared with young runners. Though vertical stiffness has not been directly investigated previously, some research has addressed its components, vertical ground reaction forces and knee flexion excursions. Previous research has indicated that older runners exhibit significantly lower knee flexion range of motion (3,11) and significantly greater peak vertical ground reaction forces than young runners (3,6). In the current study, the OLD runners exhibited both smaller peak knee flexion angles and knee flexion excursions than YOUNG runners. These factors contribute to the greater vertical stiffness values observed in older adults compared with young runners.

Investigation of load attenuation strategies in older compared with young adults in other forms of locomotion also support the current findings. Specifically, it was shown that older adults performed a downward stepping task with 50% greater stiffness compared with their young counterparts (15). These greater stiffness values were associated with smaller joint ranges of motion at the ankle and knee compared with young adults. A subsequent study revealed that these exaggerated lower extremity stiffness values observed in older adults were the result of a unique neuromuscular strategy which included greater preactivation and coactivation ratios compared with young adults (16). As a result of this modified neuromuscular strategy, older adults place a greater reliance on skeletal compared with muscular structures to absorb load during the downward stepping task (7).

In the current study, it was revealed that older adults exhibited significantly greater vertical stiffness values but no differences in vertical ground reaction forces. Therefore, the significantly smaller vertical oscillations of the center of mass during the running movement underlies the greater vertical stiffness in OLD runners. This notion is further supported by previous findings that indicated smaller peak knee flexion angles in older adults compared with their younger counterparts (11). These findings suggest that center of mass oscillations may be a clinically meaningful variable for rehabilitation professionals to consider during evaluation and treatment.

In the present study it was hypothesized that older runners would produce significantly greater joint stiffness values. In contrast to our hypothesis, the current data...
demonstrated that older runners exhibited significantly smaller dynamic joint stiffness values at both the ankle and the knee joints. Dynamic joint stiffness is a composite measure of the torque generated at a joint and the compliance of that joint represented by range of motion. It can be suggested that during running joint stiffness is the result of 2 primary components: the physical properties of the muscle-tendon unit (MTU) and neuromuscular strategy. Although no previous research has directly investigated aging and dynamic joint stiffness, it has been shown that elderly runners exhibit reductions in normalized stiffness of the knee extensor MTU during a single-joint isometric contraction (18). In the same study, however, no differences in MTU stiffness were observed in the ankle plantarflexors. A subsequent investigation focusing on age-related changes in stiffness used a level walking task to assess differences in gait biomechanics in elderly compared with young runners (19). It was revealed that elderly runners produced significantly smaller ankle plantarflexion and knee extension torques during the load response portion of the stance phase. Though not calculated in the study by Karamanidis and Arampatzis (19), the significantly smaller joint moments observed in the elderly runners would potentially also result in smaller dynamic joint stiffness values. When considered in conjunction with age-related changes in the physical properties of the MTU, it can be suggested that these age-related changes in the mechanical properties of the MTU do not entirely explain the distinct differences in joint stiffness observed between healthy young and older runners during dynamic tasks such as walking and running.

Although differences in MTU stiffness properties likely have a role in the smaller dynamic joint stiffness values observed in older runners, a potentially complimentary mechanism underlying these distinct mechanics may pertain to the unique gait parameters exhibited by these 2 groups. Specifically, it has been suggested that older adults adopt shorter step lengths compared with their young counterparts (6,11,17,19). Moreover, these elderly runners produced significantly smaller ankle plantarflexion and knee extension torques during the load response portion of the stance phase. By adopting a gait strategy that includes shorter step lengths, older adults would functionally reduce the distance between the ground reaction force vector and the lower extremity centers of joint rotation thereby reducing the ground reaction force moment arms. A strategy that limits the moment arms associated with the vertical ground reaction force would result in smaller ankle dorsiflexion and knee flexion excursions at midstance, when peak torque would occur. Reduction of the ground reaction force moment arm decreases internal joint moments and corresponding muscle forces required to prevent limb collapse during weight acceptance. However, by implementing this strategy older adults may inherently increase the skeletal component of shock attenuation. This is demonstrated by the increase in vertical stiffness in the current study and in previous research demonstrating a similar trend during a downward stepping task (7).

Although this study provides novel information regarding the effect of advancing age on lower extremity running biomechanics, several limitations do exist. One limitation of the current study pertains to a small sample size. With a total sample size of 19 divided into 2 groups (Young: N = 9; Older: N = 10), it is possible that the study lacked statistical power. However, comparisons in this study presented with robust effect sizes as evidenced by Cohen's d. A second limitation of the current study pertains to the lack of moment arm data. It is possible that older adults ran with shorter steps to minimize ground reaction force moment arms relative to joint centers, contributing to smaller dynamic joint stiffness values. Future analyses may address these limitations in an aged running population.

**Practical Applications**

Our results demonstrated that older runners exhibit greater vertical stiffness values while simultaneously producing smaller dynamic joint stiffness values when compared with younger runners. These seemingly divergent findings may be the result of the distinct running biomechanics adopted by older compared with younger adults to reduce muscular loading during running including running slower and taking shorter steps (6). These unique running biomechanics in older adults functionally reduce the vertical ground reaction force and ground reaction force moment arm resulting in smaller mechanical demands placed on the muscle.

It remains unclear if older adults experience greater skeletal loading than younger runners, however, in concert with previous research findings, the current findings may suggest that skeletal loading is greater in older compared with younger adults during a running task (7,15,16), which may predispose older runners to injuries in lower extremity structures including bony and tendon tissues. This proposed elevated risk of injury should be considered in the development of training programs for older adults. Furthermore, investigations of proposed training mechanisms to reduce stiffness in older adults and reduce skeletal loads during running should be conducted.

**References**


Age-Related Stiffness in Running

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