Age-related differences in sagittal-plane knee function at heel-strike of walking are increased in osteoarthritic patients

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Objective: To compare age-related patterns of gait with patterns associated with knee osteoarthritis (OA), the following hypotheses were tested: (H1) The sagittal-plane knee function during walking is different between younger and older asymptomatic subjects; (H2) The age-related differences in H1 are increased in patients with knee OA.

Design: Walking trials were collected for 110 participants (1.70 ± 0.09 m, 80 ± 14 kg). There were 29 younger asymptomatic subjects (29 ± 4 years) and 81 older participants (59 ± 9 years), that included 27 asymptomatic subjects and 28 and 26 patients with moderate and severe medial knee OA. Discrete variables characterizing sagittal-plane knee function were compared among the four groups using ANOVAs.

Results: During the heel-strike portion of the gait cycle at preferred walking speed, the knee was less extended and the shank less inclined in the three older groups compared to the younger asymptomatic group. There were similar differences between the severe OA group and the older asymptomatic and moderate OA groups. Both OA groups also had the femur less posterior relative to the tibia and smaller extension moment than the younger group. During terminal stance, the severe OA group had the knee less extended and smaller knee extension moment than the younger asymptomatic and older moderate OA groups.

Conclusions: The differences in knee function, particularly those during heel-strike which were associated with both age and disease severity, could form a basis for looking at mechanical risk factors for initiation and progression of knee OA on a prospective basis.

Introduction

While the etiology of idiopathic knee OA remains unclear, altered knee function during walking is thought to play an important role in the disease process. Specifically, the support for a mechanical pathway includes observations that tibial and femoral articular cartilage is conditioned to the distribution of ambulatory load in young subjects and that mature cartilage has limited adaptive capacity. This suggests that changes in knee function could modify joint loading in a manner that cartilage might be unable to accommodate and thus possibly contribute to knee OA. Biological and structural changes occur with aging and OA, and the interaction between these changes and changes in knee mechanics could also play a critical role in the disease process.

It is therefore useful to consider the nature of gait differences in the context of knee OA. Although the association between ambulatory mechanics and disease severity is of primary interest, analyzing the association with aging is also important because age is a main risk factor for idiopathic knee OA. It is well documented that as healthy individuals age they walk with slower speed, shorter stride length, and higher stance ratio in a manner similar to patients with knee OA. However, these basic gait parameters are not specific to knee function and there is a paucity of information regarding differences in knee kinetics and kinematics during walking that could be associated with both aging and knee OA. Identifying such differences would provide additional basis to better understand disease process and possibly help in designing prevention and treatment strategies.

At present the available information about the knee flexion-extension angle during walking relative to aging and OA...
severity 13–16, 20–26 clearly suggests that flexion-extension differences occur with both increasing age and OA severity. However, the contradictory results among studies preclude the identification of specific differences in knee function associated with aging and OA, thus limiting the understanding of the importance of gait mechanics in the disease process. It is particularly difficult to draw firm conclusions based on literature because the protocols differ considerably among studies (e.g., age and body size of the participants, gait aids usage, ground vs treadmill ambulation, measurement technique, location and OA severity, or walking speed) and these differences in study design are known to influence gait patterns. Therefore, there is a need to compare the knee flexion-extension angle over the entire gait cycle between individuals of different ages and OA severities in a single study controlling for inter-individual variations in possible confounding factors.

Although the knee flexion-extension angle is a key parameter in describing the angular relationship between the shank and the thigh in the sagittal-plane, it does not allow for a complete analysis of the knee function in this plane as it is possible to have similar knee flexion-extension angles but different inclinations of the thigh and shank segments. Isolating the contribution of the thigh and shank segments, which could significantly enhance the understanding and prevention of knee OA, is particularly motivated by reports that age-related decline in muscle strength 14,20–26 was associated with a distal to proximal shift in lower extremity power production 14,20–24 and reports of altered muscle activity in OA knees 26–28. These differences in muscle action also motivate the comparison of the flexion-extension moment. As with the flexion-extension angle, literature supports the existence of differences in the sagittal-plane moment with increasing age 13,19 or OA severity 13,14,16,20,24–26, but the difficulty in comparing studies limits the identification of specific differences that could be associated to either aging, OA, or both. Finally, there is also an interest in analyzing the anterior-posterior displacement of the knee (i.e., the position of the femoral condyles relative to the tibial plateau) because the differences previously observed in flexion-extension angle and moment suggest that the displacement could also differ with aging and disease 15–23, and alterations in knee displacement have been associated with risks for OA 1–2.

In summary, there are evidences supporting gait changes with increasing age and OA severity and it is possible that these changes influence cartilage health on a prospective basis. However, it would be premature to attempt a long term prospective study to evaluate the risk for OA initiation or progression without first testing if there are consistent gait differences between younger and older healthy subjects as well as between patients of similar age but with asymptomatic, moderate OA, and severe OA. Thus, the purpose of this study was to compare gait characteristics in an asymptomatic population of younger and older adults to older OA patients of different severities. The following hypotheses were tested: (H1) Sagittal-plane knee function during walking (i.e., knee angle and moment, thigh and shank inclination, and femur displacement) is different between a younger and an older group of asymptomatic subjects; (H2) The age-related differences in H1 are increased in patients with moderate OA compared to asymptomatic subjects, and are further increased in severe OA compared to moderate OA patients.

Materials and methods

Participants

One hundred and ten individuals participated in this study after providing IRB-approved informed consent. Participants, recruited from the orthopedic clinic or from the community using printed flyers, were placed in one of four groups (younger asymptomatic, older asymptomatic, older moderate OA, and older severe OA) based on their age and disease severity (Table I). Inclusion criteria for the OA patients were: medial knee OA diagnosed by a clinician; self-reported pain in the medial compartment of the knee during at least half of the days of the previous month; ability to walk without aids; and 40 years of age or older. Exclusion criteria were: diagnosed or symptomatic OA in other lower extremity joints; gout or recurrent pseudogout; intraarticular joint injection during the previous 2 months; total

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of knees</th>
<th>OA severity</th>
<th>Side</th>
<th>Gender</th>
<th>Age, year</th>
<th>Height, m</th>
<th>Weight, kg</th>
<th>BMI, kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Younger asymptomatic</td>
<td>29</td>
<td>Asymptomatic</td>
<td>L, 16 R</td>
<td>17 M, 12 F</td>
<td>29.2 ± 4.3</td>
<td>1.71 ± 0.08</td>
<td>79.8 ± 13.2</td>
<td>27.4 ± 4.0</td>
</tr>
<tr>
<td>Older asymptomatic</td>
<td>27</td>
<td>Asymptomatic</td>
<td>L, 16 R</td>
<td>15 M, 12 F</td>
<td>56.7 ± 7.5</td>
<td>1.69 ± 0.06</td>
<td>78.3 ± 10.7</td>
<td>27.4 ± 3.0</td>
</tr>
<tr>
<td>Older moderate OA</td>
<td>28</td>
<td>18 KLG1, 10 KLG2</td>
<td>L, 14 R</td>
<td>15 M, 13 F</td>
<td>58.1 ± 8.8</td>
<td>1.70 ± 0.10</td>
<td>79.1 ± 15.5</td>
<td>27.3 ± 4.5</td>
</tr>
<tr>
<td>Older severe OA</td>
<td>26</td>
<td>12 KLG3, 14 KLG4</td>
<td>L, 15 R</td>
<td>10 M, 16 F</td>
<td>62.3 ± 9.6</td>
<td>1.69 ± 0.11</td>
<td>83.7 ± 15.8</td>
<td>29.3 ± 5.3</td>
</tr>
</tbody>
</table>

Data are presented as mean ± standard deviation. KLG stands for Kellgren/Lawrence grade and BMI for body mass index.

### Table I
Population demographics

<table>
<thead>
<tr>
<th>Curve</th>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexion-extension angle</td>
<td>KFAhs</td>
<td>Maximum extension angle around heel-strike</td>
</tr>
<tr>
<td></td>
<td>KFAsm</td>
<td>Maximum flexion angle during midstance</td>
</tr>
<tr>
<td></td>
<td>KFAsw</td>
<td>Maximum flexion angle during terminal stance</td>
</tr>
<tr>
<td></td>
<td>KFAsw</td>
<td>Maximum flexion angle during swing</td>
</tr>
<tr>
<td></td>
<td>KFAsw − KFAsm</td>
<td>Range of motion between KFAsm and KFAms</td>
</tr>
<tr>
<td></td>
<td>KFAms − KFAsw</td>
<td>Range of motion between KFAsw and KFAms</td>
</tr>
<tr>
<td>Femur anterior—posterior displacement</td>
<td>FADms</td>
<td>Maximum posterior displacement around heel-strike</td>
</tr>
<tr>
<td></td>
<td>FADsw</td>
<td>Maximum anterior displacement during swing</td>
</tr>
<tr>
<td>Thigh backward—forward inclination</td>
<td>TBIsw</td>
<td>Maximum forward inclination during terminal stance</td>
</tr>
<tr>
<td></td>
<td>TBIms</td>
<td>Maximum backward inclination during swing</td>
</tr>
<tr>
<td>Shank backward—forward inclination</td>
<td>SBIsw</td>
<td>Maximum backward inclination around heel-strike</td>
</tr>
<tr>
<td></td>
<td>SBIms</td>
<td>Maximum forward inclination during swing</td>
</tr>
<tr>
<td>Knee flexion-extension moment</td>
<td>KFMhs</td>
<td>Maximum extension moment around heel-strike</td>
</tr>
<tr>
<td></td>
<td>KFmsm</td>
<td>Maximum flexion moment during midstance</td>
</tr>
<tr>
<td></td>
<td>KFMms</td>
<td>Maximum extension moment during terminal stance</td>
</tr>
</tbody>
</table>

The abbreviations hs, ms, ts, and sw respectively correspond to the heel-strike, midstance, terminal stance, and swing portions of the gait cycle.
The abbreviations stepped on the forceplate. Knee kinematics and kinetics were trial was considered successful when the foot of the test leg fully walking across the lab until three successful trials were collected. A than their preferred speed, and walking speed was not controlled: Columbs, OH) were used to record the trials at 120 Hz. Walking forceplate embedded in the middle of the walkway (Bertec, patients were tested in their own walking shoes. An optoelectronic walking speed, as well as slower and faster trials. Footwear is known to in

Asymptomatic group otherwise.

The column on the right presents the

Tukey tests are indicated by superscript symbols (#: different from younger asymptomatic, : different from older asymptomatic, #: different from older moderate OA, n: different from older severe OA (P < 0.008)).

The abbreviations hs, ms, ts, and sw respectively correspond to the heel-strike, midstance, terminal stance, and swing portions of the gait cycle.

Knee replacement in either knee; serious ankle, hip, or back injury or surgery; and older than 80 years of age. The study protocol did not include collection of radiographic images, instead patients were asked to come with recent conventional clinical weight-bearing extended knee radiographs. A senior Orthopedic Surgeon read the X-ray to confirm that the OA was primarily in the medial compartment (knees with primarily lateral or trochlea OA were excluded), and to determine Kellgren/Lawrence grade (KLG)32. Only the index knee of each OA patient, defined as the knee with more severe radiographic OA or the most painful knee in case of similar KLG for both knees, was analyzed in this study. OA patients were placed in the older moderate OA group if the KLG of their index knee was 1 or 2, and they were placed in the older severe OA group if their index knee KLG was 3 or 4.

Asymptomatic subjects were included if they were between 20 and 80 years of age and had no self-reported chronic pain or serious lower extremity or back injury or surgery. One randomly selected knee per asymptomatic subject was analyzed in this study. Asymptomatic subjects were placed in the younger asymptomatic group if they were less than 40 years of age, and placed in the older asymptomatic group otherwise.

Gait analysis

Participants performed walking trials of 10 m at their preferred walking speed, as well as slower and faster trials. Footwear is known to influence knee mechanics. Therefore, to get measures reflecting the natural function of the knee with higher fidelity, patients were tested in their own walking shoes. An optoelectronic motion capture system (Qualisys Medical, Gothenburg, Sweden) and a forceplate embedded in the middle of the walkway (Bertec, Columbs, OH) were used to record the trials at 120 Hz. Walking speed was not controlled: first patients were asked to walk at a self-selected comfortable (i.e., preferred) speed, then to walk slower than their preferred speed, and finally to walk faster than their preferred speed. For each speed requirement, the patients kept walking across the lab until three successful trials were collected. A trial was considered successful when the foot of the test leg fully stepped on the forceplate. Knee kinematics and kinetics were determined following previously described methods34,35 using the software application BioMove (Stanford University, CA). Briefly, the position and orientation of the foot, shank, and thigh segments were calculated using clusters of reflective markers fixed to the participant32,34. The segments’ anatomical frames were determined following a previously described procedure32 during a standing reference pose collected before the walking trials. The kinematics of the knee in the sagittal-plane were described by the flexion-extension anglefi, the anterior–posterior displacement of the femur relative to the tibia (i.e., the position of the center of the transepicondylar axis along the anterior–posterior axis of the tibial anatomical frame; note: this measure should not be confused with the displacement of the tibiofemoral contact point)fi, and the backward–forward inclination of the thigh and shank segments (i.e., the angle between the longitudinal axis of the segment and the vertical axis calculated in the sagittal-plane of the segment). A positive displacement indicates that the center of the transepicondylar axis is anterior to the origin of the tibial anatomical frame and a positive inclination indicates that the segment is tilted backward. The external knee flexion-extension moment was calculated using a standard inverse dynamics approach and was normalized to percent bodyweight and height (%BW*Ht) to allow for comparison between individuals.

For each trial, the heel-strike events corresponding to the beginning (0%) and to the end (100%) of the gait cycle in the middle of the walkway were identified and used to normalize the five kinematic and kinetic signals (i.e., knee angle and moment, femur displacement, and thigh and shank inclinations) to 101 samples between −5% and 95% of the gait cycle. The analysis window started at −5% of the gait cycle to facilitate the extraction of peak features from the five normalized curves and to enhance the interpretation of knee function around heel-strike. Additionally, 15 characteristic amplitudes were measured along the five normalized curves for each trial (Table II).

Statistical analysis

To test the hypotheses, one-way ANOVAs were done to determine if the 15 kinematic and kinetic variables (Table II) were
significantly different among the four participant groups. One-way ANOVAs were also performed on four basic spatiotemporal variables (walking speed, cycle duration, stance ratio, and stride length) to compare the general gait mechanics among groups. The significance level for these tests was set at 5% with Bonferroni correction for the comparisons of 19 variables ($\alpha = 0.003$). When necessary, post hoc Tukey tests were used to detect significant differences within the six group combinations ($\alpha = 0.008$). For this analysis, the gait variables collected during the trials at preferred speed were averaged for each participant and the ANOVAs were performed based on one average data point per participant and gait variable.

Additionally, group average curves were calculated for the knee flexion-extension angle, femur anterior–posterior displacement, thigh and shank backward–forward inclinations, and knee flexion-extension moment at preferred walking speed. To this end, the curves of the trials at preferred speed were first averaged for each participant. Next, the average curves of all the participants in a group were averaged to obtain the group average curves.

Finally, one-way ANOVAs ($\alpha = 0.05$) and post hoc Tukey tests ($\alpha = 0.008$) were performed to compare the demographics among the four groups. All data processing was done with Matlab version R2010b (Mathworks, MA).

### Results

The four groups of participants were of comparable size (Table I) and there were no significant differences in height ($P = 0.188$), weight ($P = 0.52$), and body mass index (BMI) ($P = 0.26$) among groups. The younger asymptomatic group was significantly younger than the three other groups ($P < 0.001$).

At preferred walking speed, there were significant and consistent differences in knee function among the four groups during the heel-strike and terminal stance portions of the gait cycle (Table III & Fig. 1). Specifically, during the heel-strike portion, the knee was significantly less extended in the three older groups compared to the younger asymptomatic group, and was also significantly less extended in the older severe OA group compared to the older asymptomatic and moderate OA groups (Table III; $\text{KFA}_{hs}$ variable). Both OA groups had the femur significantly less posterior relative to the tibia ($\text{FAD}_{hs}$) in comparison to the femur displacement in the younger asymptomatic group. There were also differences in backward shank inclination ($\text{SBH}_{hs}$), with the shank significantly less inclined (more vertical) in the three older groups than in the younger asymptomatic group and the shank less inclined (more vertical) in the older severe OA group than in the two other older groups. The knee extension moment ($\text{KFM}_{hs}$) of both OA groups was significantly smaller than the knee extension moment of the younger asymptomatic group. During terminal stance, the older severe OA group had the knee significantly less extended ($\text{KFA}_{ts}$) and smaller knee extension moment ($\text{KFM}_{ts}$) than the younger asymptomatic and the older moderate OA groups. Interestingly, while increasing age and disease severity was associated with less extension ($\text{KFA}_{hs}$ and $\text{KFA}_{ts}$), there were no significant differences among groups regarding maximum flexion during either midstance ($\text{KFM}_{ms}$) or swing ($\text{KFM}_{sw}$) phases. These differences in peak extension but not in peak flexion resulted in smaller ranges of motion ($\text{KFM}_{ms}$–$\text{KFA}_{ms}$ and $\text{KFM}_{sw}$–$\text{KFA}_{sw}$) for the older severe group compared to the three other groups.

There were also group differences in spatiotemporal variables (Table III). The older severe OA patients walked significantly slower than the younger asymptomatic subjects. The slower walking speed was associated with a significantly shorter stride length compared to the younger asymptomatic subjects and a significantly higher stance ratio than the three other groups.

To better interpret the group differences during walking, the kinematic variables were also compared during the standing posture used to define the biomechanical model. This secondary analysis showed that, during standing, the knee was significantly more flexed in the severe group compared to the three other groups, mainly due to more forward inclination of the shank in the severe OA patients (Table IV). Less thigh forward inclination (significant for the young and moderate groups) also contributed to the larger flexion angle observed in the severe group. Conversely, there were no differences in femur displacement among groups during standing.

### Discussion

The results of this study demonstrating that there were specific age-related gait differences that were increased in patients with more severe OA provided new insight into disease pathomechanics. Specifically, the study suggested that the portions of the gait cycle when the knee goes into extension, particularly around heel-strike, could be important in terms of differences related to aging and OA. Additionally, the results highlighted specific gait markers that could form a basis for looking at risk factors for initiation or progression of knee OA on younger asymptomatic subjects. Such longitudinal research would be well supported by a growing body of literature about the potential for specific gait measures to influence cartilage health$^{1–4}$. Furthermore, by analyzing the complete gait cycle of participants of varying age and OA severity, this study helped interpret the results of prior studies that reported inconsistent differences in knee flexion angle and moment with increasing age$^{5–12,17–19}$ or disease severity$^{13–16,20–26}$.

During the heel-strike portion of the gait cycle, knee extension decreased from the younger asymptomatic group through the older asymptomatic and moderate OA groups, and to the severe OA groups, as illustrated in Fig. 2. By analyzing the segment inclination, this study showed that the difference was due to the shank being less tilted with increasing age and disease severity. This observation is consistent with previously described age-related decline in quadriceps strength$^{24,37}$ and distal to proximal shift in lower extremity power production during walking$^{12,29}$. Altered muscle activity is well documented in aging subjects and OA patients, mainly increased co-activation and hamstring-to-quadriceps ratio$^{21,29–31}$.38 These differences in function between extensor and flexor muscles agree with the finding of less knee extension in older subjects and OA patients. Muscle function is closely related to joint kinematics. Specifically, when the quadriceps contracts it tends to pull the tibia anteriorly relative to the femur, which is measured as a negative knee displacement. Conversely, when the hamstring contracts it pulls the tibia posteriorly relative to the femur, which is measured as a positive knee displacement. A change in muscle activity in favor of the hamstring (compared to the quadriceps) would be associated with positive knee displacement, thus supporting the results of less posterior displacement of the femur in older and diseased knees. These consistent results provide a basis for further exploration of gait changes as a factor in the increased incidence of knee OA with aging or in disease progression.

While longitudinal studies are required to show any causality between the differences in knee function around heel-strike identified in this study and knee OA, it is useful to mention that a recent study estimated that a decrease of 5° in maximum knee extension around heel-strike ($\text{KFM}_{ms}$) corresponds to a posterior shift in the location of the thickest cartilage point on the medial condyle equivalent to 18% of the length of the load-bearing region$^4$. On average, the younger and older asymptomatic groups in the present study differed by 4.1° and the older asymptomatic and severe OA groups by 4.6°. Therefore, since the spatial distribution of
Fig. 1. Kinematic and kinetic average curves for the four groups of participants at preferred walking speed. To highlight the differences among groups around heel-strike, the curves are displayed between −5 and 95 % of the gait cycle; the dashed vertical line in each graph corresponds to the heel-strike event (0% of the gait cycle). The gray areas indicate the
post hoc after reconstruction of the anterior cruciate ligament 42, 43 or reduced knee extension around heel-strike has also been reported it is possible that the differences in knee function around the terminal stance. However, these differences were only between the severe OA group and the three other groups, suggesting that a knee less extended and a smaller knee extension moment during terminal stance might be an effect or a compensation for osteoarthritis of the knee rather than a cause or a consequence of disease initiation. In literature, a stiffer knee during push-off was suggested to be adopted by OA patients possibly to increase knee stability, reduce external load on the joint, and reduce pain 44, 45. Interestingly, while this study analyzed the complete gait cycle, nearly all the differences were observed during the two portions of the gait cycle when the knee is extended. It is possible that age-related differences in soft-tissue properties 27, 45 as well as pain in OA knees provide more options for adaptation in extension than in flexion. These two portions almost align with periods of double support. So it is also possible that they offer more options for adaptation since both feet are in contact with the ground during that time, thus reducing the consequences of functional adaptations on balance and gait performance 6, 46.

Walking speed should always be considered when comparing gait variables because it can affect knee function 47. Therefore, a supplementary analysis was done where the gait variables were compared at the same normalized walking speed for all participants instead of at a different preferred speed for each patient (see Supplementary Materials). This analysis showed consistent group differences for both speed conditions, indicating that there were functional differences among the four groups beyond the differences in walking speed. Future research is necessary to identify the causes of these functional differences, but these results suggested that age-related decrease in motor control 8, 12, 29, 46, muscle strength 24, 47, and soft-tissue properties 27, 45 are probably key factors because they can affect both the movement of the knee joint and walking speed.

During standing, the knees with severe OA were less extended than all other knees. This result agreed with literature which has frequently reported flexion contracture in OA joints, usually defined as an inability to fully extend the knee while lying on an exam table 48. These observations of limited knee extension during standing and lying postures are consistent with the gait results in this study, where all significant differences were in the form of less knee extension with increasing age and disease severity. Flexion contracture was previously associated with quadriceps weakness and shortening of muscle tissue, as well as ligament stiffness, swelling, and pain 8, 45. Interestingly, while the standing posture only revealed differences with the severe OA group, differences between the younger and older asymptomatic groups and differences between the moderate and severe OA groups were detected during walking. This higher sensitivity during a dynamic activity supported the idea that decrease in motor control 8, 12, 29, 46, muscle strength 27, 47, and soft-tissue properties 27, 45 could be primary factors for the functional knee differences observed in this study. The importance of these three factors over swelling or pain was further

cartilage thickness has been shown to be finely conditioned to ambulatory load 6, 39 and mature cartilage has limited adaptive capacity 5, it is possible that the differences in knee function around heel-strike are large enough to influence knee OA. This possibility is further supported by reports of high joint load during this portion of the gait cycle in asymptomatic subjects 40, 41, and by altered muscle activations which might even increase the loading at the knee in the older groups. Moreover, in a knee that is less extended at heel-strike and has similar maximum knee flexion during midstance (i.e., reduced KFAms−KFAhs range of motion), the area over which the joint load can be distributed is smaller. Interestingly, reduced knee extension around heel-strike has also been reported after reconstruction of the anterior cruciate ligament 24, 43 or meniscectomy 25, two conditions that lead to higher risk of knee OA, further supporting the possible role of altered knee function during this period of the gait cycle in OA of the knee. This study also indicated differences in knee function during terminal stance. However, these differences were only between the severe OA group and the three other groups, suggesting that a knee

<table>
<thead>
<tr>
<th>Table IV</th>
<th>Knee kinematics during standing posture</th>
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</thead>
<tbody>
<tr>
<td>Younger asymptomatic (n = 29)</td>
<td>Older asymptomatic (n = 27)</td>
</tr>
<tr>
<td>Knee flexion angle, °</td>
<td>−3.1 (−5.1; −1.1) °</td>
</tr>
<tr>
<td>Femur anterior displacement, mm</td>
<td>4.9 (3.8; 5.9)</td>
</tr>
<tr>
<td>Thigh backward inclination, °</td>
<td>−5.0 (−5.9; −4.1) °</td>
</tr>
<tr>
<td>Shank backward inclination, °</td>
<td>−1.9 (−3.3; −0.6) °</td>
</tr>
</tbody>
</table>

Data are presented as mean and 95% confidence intervals (lower limit; upper limit). The column on the right presents the p-value of the ANOVA tests comparing the four groups. In case of significant differences among groups (bold p-values), the results of the post hoc Tukey tests are indicated by superscript symbols ( #: different from younger asymptomatic, *: different from older asymptomatic, #: different from older moderate OA, °: different from older severe OA (P < 0.008)).
strengthened by the fact that extension differences were noticed between two asymptomatic groups, which were equally free of swelling and pain.

The findings of this study must be interpreted in the context of its limitations. First, it is possible that some asymptomatic subjects had undiagnosed knee OA as no radiograph was available for those participants. Nevertheless, this should only modestly affect the overall conclusions of the study because the probability is high that undiagnosed OA individuals would be in the older asymptomatic group and have less severe OA than the patients in the moderate OA group, therefore maintaining the order among the four groups. Furthermore, the consistent differences with increasing age and OA severity in the present study corroborated a trend in previous gait studies comparing flexion-extension angle or moment between groups with different age10,12,15 or OA severity5,10,16,20,21,26. However, it is impossible to exclude that the absence of differences between the older asymptomatic and moderate OA groups could be due to the presence of knees with undiagnosed OA in the older asymptomatic group. Second, this study was a cross-sectional design and included knees with medial OA only. While medial OA is more frequent than lateral OA10, further studies are necessary to extend these results to all types of OA. Similarly longitudinal studies should demonstrate if changes in knee function due to either increasing age or OA severity are predictive of disease onset and progression. Furthermore, as in any gait study, the inter-participant variability was relatively high, suggesting that longitudinal studies testing the changes with aging or disease progression should be considered in the future to confirm a potential mechanical pathway. A central question to be answered is whether patients with early OA had larger changes in knee function over the years or decades preceding disease onset than asymptomatic subjects of similar age. There are differences in the development of knee OA between males and females, therefore future studies should be performed to test for differences in ambulatory knee function by gender. Multi-disciplinary research is also required to understand the role and interaction with biological and structural factors5,14. Finally, while a technique shown to minimize soft-tissue artifact12,34,35,42 was used to quantify knee function, one cannot exclude some measurement error. However, since the study included a large cohort of participants who were equally exposed, it is very unlikely that the consistent group differences were due to measurement errors. On the other hand, it is possible that these errors masked other group differences.

In conclusion, this study identified age-related differences in knee function around heel-strike which were increased in knees with severe OA. Differences between the severe OA group and the three other groups were also identified during the terminal stance portion of the gait cycle and during standing posture. Additionally, it was shown that functional differences were not uniquely attributable to differences in walking speed. This study helped connect the differences associated with increasing age and increasing disease severity, therefore bringing new insights regarding the importance of knee mechanics in idiopathic OA.

Author contribution statement

JF: conception and design, obtaining of funding, collection and assembly of data, analysis and interpretation of the data, drafting of the article, critical revision of the article for important intellectual content, final approval of the article.

TPA: conception and design, obtaining of funding, analysis and interpretation of the data, drafting of the article, critical revision of the article for important intellectual content, final approval of the article.

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Competing interest statement

There were no conflicts of interest for any of the authors.

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.joca.2013.12.014

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