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Age has a minimal effect on knee kinematics: A cross-sectional 3D/2D image-registration study of kneeling

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ABSTRACT

Introduction: Kneeling is an activity of daily living which becomes difficult with knee pathology and increasing age. This study aimed to capture kneeling kinematics in six-degrees-of-freedom in healthy adults as a function of age.

Methods: 67 healthy knee participants aged from 20 to 90 years were categorised into four 20-year age-groups. 3D knee kinematics were captured using 3D/2D image-registration of CT scan and fluoroscopy during kneeling. Kinematic variables of position, displacement and rate-of-change in six-degrees-of-freedom were compared between age-groups while controlling for University of California Los Angeles activity scale and the Assessment of Quality of Life physical score.

Results: Over the entire kneeling cycle there were few differences between the age-groups. Results are reported as pairwise contrasts. At 110° flexion, 80+ knees were more varus than 20–39 and 40–69 (4.9° (95%CI: 0.6°, 9.1°) and 6.4° (2.1°, 10.7°), respectively). At 120° flexion, the 80+ age-group femur was 5.5 (0.0, 11.0) mm more anterior than 20–39. Between 120° to maximum flexion, 80+ knees rotated into valgus more than 20–39, 40–59 and 60–79 (5.5° (1.2°, 9.8°); 5.5° (1.1°, 9.8°); and 4.5° (0.9°, 7.5°), respectively).

Conclusion: This is the first study to report kneeling knee kinematics of ageing using 3D/2D image registration. We found that ageing does not change knee kinematics under 80 years, and there are minimal changes between 120° and maximum flexion between the younger and 80+ age-groups. Thus, difficulty kneeling should not be considered to be an inevitable consequence of ageing.

1. Introduction

Understanding the tibiofemoral kinematics of kneeling and how it may change as we get older, will assist with: clinical evaluation, assessment of surgical outcomes, the evaluation of rehabilitation outcome measures for diseases such as knee osteoarthri-

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tis (KOA), along with knee simulation studies and functional designs of total knee replacements (TKR) [1–8]. Kneeling requires deep knee flexion and is associated with activities of daily living, including expressions of reverence [9–11].

Early studies have investigated tibiofemoral kinematics of dynamically loaded deep-flexion, with activities including squatting [12–14], lunging [1,3,15–20], and kneeling [21–23]. However, a 2018 systematic review and meta-analysis of healthy tibiofemoral kinematics found kneeling is the least investigated deep flexion activity [10].

Studies of kneeling have used a range of methods including bi-planar radiographs [21], motion capture with skin markers [23], and a combination of MRI (magnetic resonance imaging),″ CT (computed tomography) and fluoroscopy [22,24,25]. Hefzy et al. used a sagittal X-ray in 2D and reported maximum flexion (maxflex). Moro-oka et al. reported external femoral rotation and posterior femoral translation, and Acker et al., reported rotation. For post total knee replacement kneeling, Nakamura et al. and Nakamura et al., used a combination of fluoroscopy and 3D model to report on the importance of the medial flexion gap to post-operative knee kinematics, and kinematics of tri-condylar total knee replacement. To date, no study has reported healthy kneeling kinematic data in six-degrees-of-freedom [10]. Six-degree-of-freedom knee kinematics will illuminate the role of each translation and rotation that contributes to full knee flexion.

The effects of ageing on tibiofemoral kinematics during kneeling have previously only been studied using motion-analysis with skin-mounted markers. These studies showed no kinematic differences between young (≤ 30 years) and elderly (≥60 years) groups [26]. However, large errors are associated with the methodology due to soft tissue and skin movement artefact [27]. With our technology, we can examine kneeling with an accuracy of 0.2 mm and 0.3° in the frontal plan, allowing us to explore differences associated with age more accurately than ever before [28].

The primary objective of this study was to measure tibiofemoral kinematics during kneeling in six-degrees-of-freedom as a function of age. The secondary objective was to develop a normative data set for populations aged 20 to 90 years. Based on previous studies, we hypothesised that getting older is associated with:

1. Decreased maximum flexion, indicating knee stiffness
2. Decreased posterior femoral position and translation, indicating decreased roll back
3. A more medially positioned femur on the tibial plateau
4. Decreased superior femoral position and translation, indicating narrowed joint space
5. Decreased external femoral angles and rotation, indicating limited mobility of the femur to rotate during flexion
6. Increased knee varus

2. Methods

This study is a cross-sectional, observational study which is a subset of the randomised controlled trial titled: A prospective imaging study of cruciate-retaining, cruciate-substituting, and rotating-platform knee replacement, in osteoarthritis and healthy ageing; (PICKLeS) #ISRCTN75076749.

This study received human research ethics approval from both ACT Health (ETH.4.11.071) and University of Canberra. Sixty-seven participants with healthy knees, over 20 years-of-age were recruited and gave informed consent to participate. Box 1 details the inclusion and exclusion criteria. (Box 1)

Box 1
Healthy participant inclusion and exclusion criteria.

Inclusion criteria

1. At least one pain free knee
2. No history of knee injury or arthritis

Exclusion criteria

1. BMI > 38kg/m^2
2. UCLA score of ≤2 (Wholly inactive or severely restricted to the minimum of activities of daily living)
3. A psychosocial reason not to be able to consent or complete the requirements of the study
4. Metastatic disease
5. Pathological fracture
6. Poor understanding and is unable to provide informed consent
7. Pregnancy
8. Unable to attend due to distance

BMI: body mass index, UCLA: University of California, Los Angeles activity score

2.1. Data collection

Participant response, performance, and observer bias were controlled by informing participants about data de-identification, standardising kneeling instructions, and the objective nature of the image registration process.

The Kellgren-Lawrence (KL) grade was used to identify osteoarthritic features and assign a grade of 0 to 4, where 0 signifies no osteoarthritis, and 4 signifies severe osteoarthritis [29]. The KL grade was determined from supine CT scans. Pairs of researchers independently graded each CT scan with discussion resolving differences. Kendall's W was used to determine the level of agreement between four researchers on the KL grade. Agreement was excellent; W = 0.965, $p < 0.0005$.

Patient recorded outcome measures were collected from all participants. They included the Function Comorbidity Index (FCI) [30], the University of California Los Angeles activity index (UCLA) [31], and the assessment of quality of life (AQoL) [32] divided into physical, mental and total utility scores.

2.1.1. Measuring kinematics using image registration

A 3D image of the knee was acquired using a Toshiba Aquilion spiral CT scanner (Toshiba Medical Systems, Japan) which reconstructed each 1 mm slice at 512×512 voxels with spatial dimensions $0.625 \times 0.625 \times 0.5$ mm^3 and 16 bits/pixel. The CT scan captured an image approximately from 150 mm above to 150 mm below the knee joint. Each participant lay supine within the CT scanner, with the test knee placed within a calibration box. The calibration box was used to calculated voxel shape in spiral CT and correct for distortion in fluoroscopy.

Kneeling was recorded using a curved panel fluoroscopy system (AXIOM-Artis, Siemens) at 30 Hz, with 1024×1024-pixel spatial resolution and 12 bits/pixel. Parameters for this system included 1200 mm between tube source and image intensifier, a screen size of 280 mm, and no filter disc on the image intensifier. We positioned the participant within the c-arm of the fluoroscopy machine with their knee on a box, with their tibia horizontal and the hip above their knee at approximately 90° knee flexion. Their foot was free to rotate over the end of the box (Figure 1). One full cycle of kneeling began upright at 90° flexion, progressed to kneeling as deeply as possible and then returned to the start. Each cycle took approximately 10 s, producing about 300 fluoroscopy frames. Verbal instructions controlled timing, and each participant had at least one opportunity to practice before image acquisition. Lead aprons were worn by the participants during the procedure, protecting from ionising radiation.

2.2. Data processing

2.2.1. Registration

Orthovis is a single-plane fluoroscopy 3D–2D multi-modal registration method of capturing knee kinematics, developed through a collaboration between University of New South Wales and Trauma and Orthopaedic Unit at the Canberra Hospital [33].

The 3D CT was first transformed into a 2D-digitally-reconstructed-radiograph (DRR) with enhanced edges. To produce the DRR, the first step within Orthovis© was to extract the femur and tibia separately from the CT. Next, the CT was segmented, which involved removing all information from every frame of the CT that was not the bone of interest. Then the DRR was achieved by simulating the capture of the fluoroscopy image of the CT and using a projective transform. Orthovis© then spatially-matched the DRR to each fluoroscopy frame using a gradient descent algorithm and the sum of conditional variances, to register the edges (Figure 2). The registration of the DRR onto each fluoroscopy frame produced a dynamic 3D image of the knee joint.

Knee kinematics were quantified in six-degrees-of-freedom in MATLAB 9.1 R2016b. Orthogonal axes were derived using the Grood and Suntay (G&S) coordinate system, as recommended by the International Society of Biomechanics [34]. Grood and

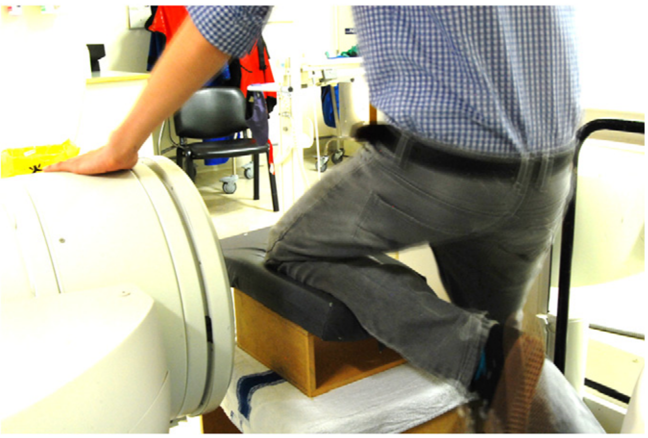


Figure 1. Kneeling on the box with the foot free to rotate. Hand placed on fluoroscopy equipment was for balance, not for taking the weight. The contralateral leg was kept behind to stay out of field-of-view. This photo was for illustration purposes, and so no apron was required.

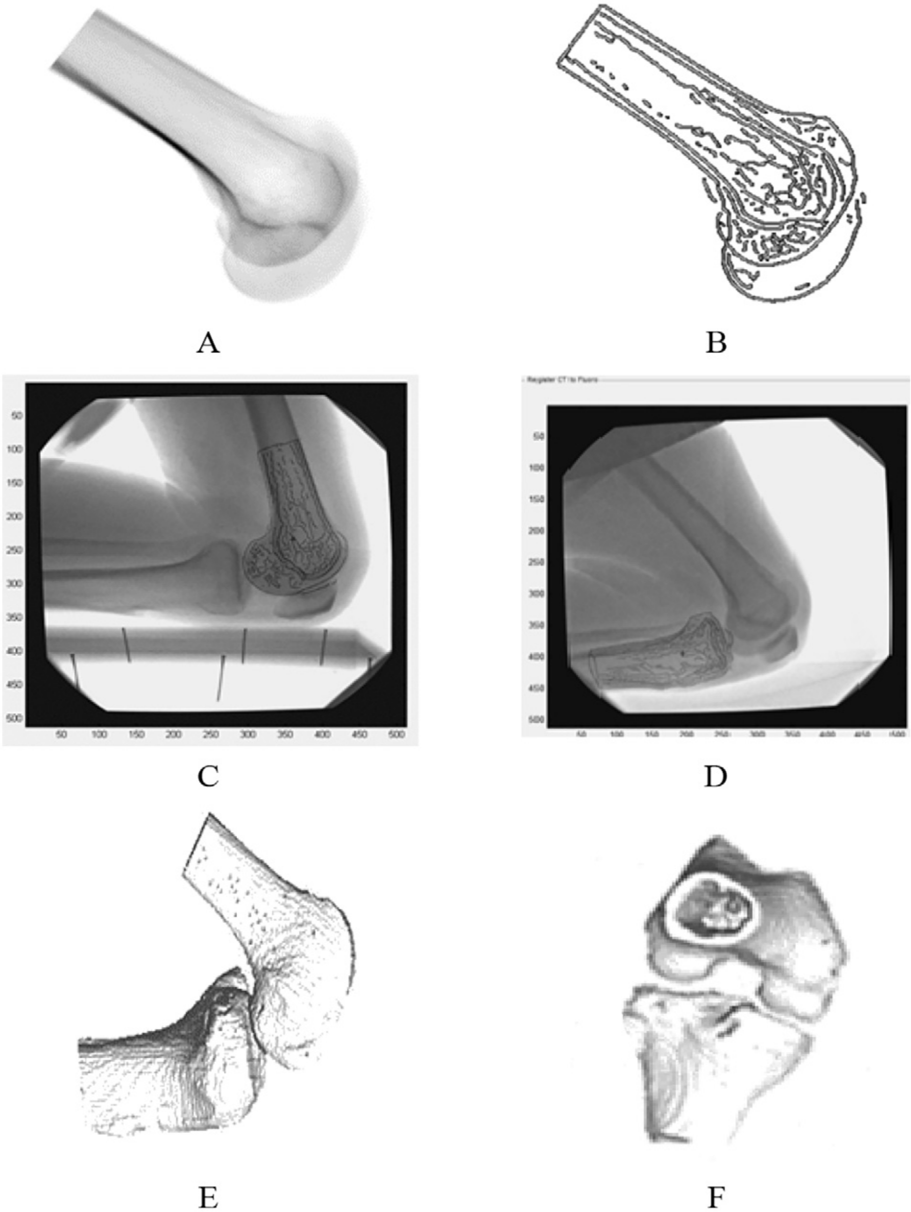


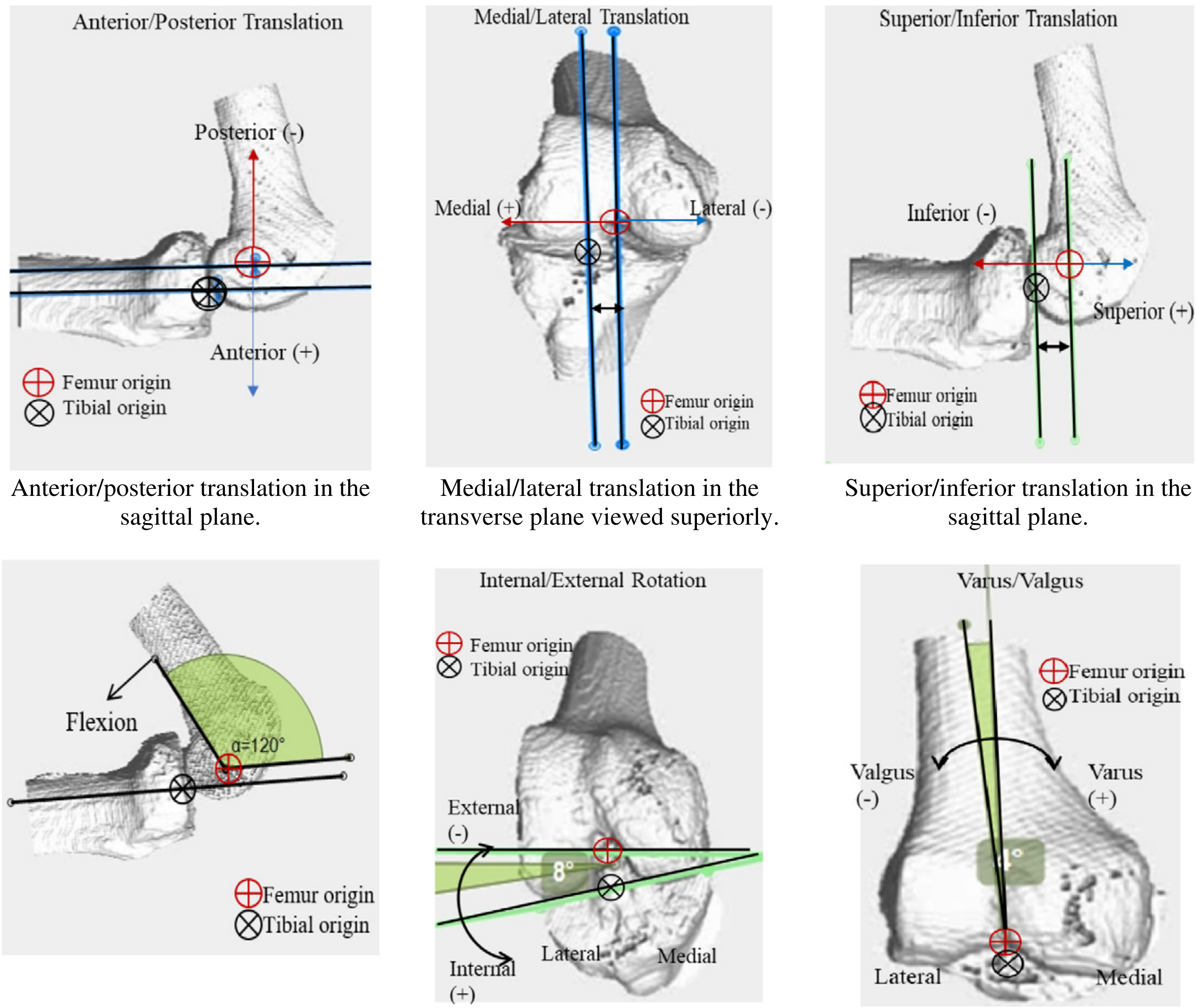
Figure 2. Orthovis© registration. A. A digitally reconstructed radiograph (DRR) of the femur made from a CT; B. DRR with enhanced edges; C. Registration of a DRR femur onto the fluoroscopy; D. Registration of DRR tibia registered onto a fluoroscopy; E. The 3D visualisation of the joint; F. The 3D image can be manipulated in Orthovis© to enable observation from any angle.

Suntay specify the relative position of the femur and tibia, by fixing a cartesian coordinate system to each bone using anatomical landmarks and defining a third 'floating' axis that moves relative to the two fixed bone axes. The relative joint geometry and motion is based on the location of the origins in the femur and tibia. The femoral origin is the most proximal point of the intercondylar notch, and the tibial origin is at the centre of the tibial eminence. An in-depth description of the method used to identify the Grood and Suntay axes is included in the supplementary material.

The six-degrees-of-freedom measured were three rotations: flexion, internal/external, and varus/valgus, and three translations: anterior/posterior, lateral/medial and superior/inferior. The directions of the kinematic variables are shown in Figure 3 and are defined as the movement of the femur relative to the tibia. Orthovis has the in-plane precision of 0.2 mm translation and 0.3°, while the out-of-plane precision was 0.9 mm and 0.5° [28].

2.2.2. Phase identification

The first order derivative inflexion points defined the phases of the kneeling cycle. These identified the start and finish of a cycle of kneeling (Figure 4).



Anterior/posterior translation in the sagittal plane.

Medial/lateral translation in the transverse plane viewed superiorly.

Superior/inferior translation in the sagittal plane.

120° flexion in the sagittal plane.

Internal/external rotation in the coronal plane.

Varus/valgus in the coronal plane.

Figure 3. Interpretation of Grood and Suntay reference system for kneeling. Six-degree-of-freedom kinematic variables showing the femoral and tibial origins, and positive and negative directions, as measured using Orthovis multimodal 3D/2D registration.

2.3. Statistical methods

Participants were categorised into four age-groups (20–39 years, 40–59 years, 60–79 years, and 80 + years). Continuous data were summarised as mean and standard deviation. Differences in group characteristics were analysed using one-way ANOVA, a chi-square test for sex and Kruskal–Wallis for KL scores.

To determine differences in kinematics between the age-groups, one-way MANCOVA analyses with UCLA activity scale and the AQoL (physical) score as covariates, were conducted to identify differences between position and displacement. All significant differences were followed up with one-way ANCOVAs and a Bonferroni post hoc test; producing pairwise comparisons of the adjusted means between the age-groups. A Bonferroni correction was made. We assessed all eleven assumptions for the one-way MANCOVA.

The rate-of-change of a kinematic variable tells us how fast the femur is moving per-degree-of-flexion (/°flexion) (slope of the graphs in Figure 5 and Figure 6). The rate-of-change (/°flex) kinematic variables did not meet MANCOVA assumptions, and so were assessed by non-parametric Kruskal-Wallis tests. The Kruskal–Wallis test assumptions were tested before the rate-of-change statistical analysis. Finally, pairwise comparisons were performed using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons for all significant differences (Table 4) [35].

Kinematic positions were compared every 10°, from 90° to maximum flexion (maxflex) over the full kneeling cycle. Displacement (translation or rotation) and rate-of-change (/°flex) kinematics were compared over flexion range 90° to 120°, 120° to

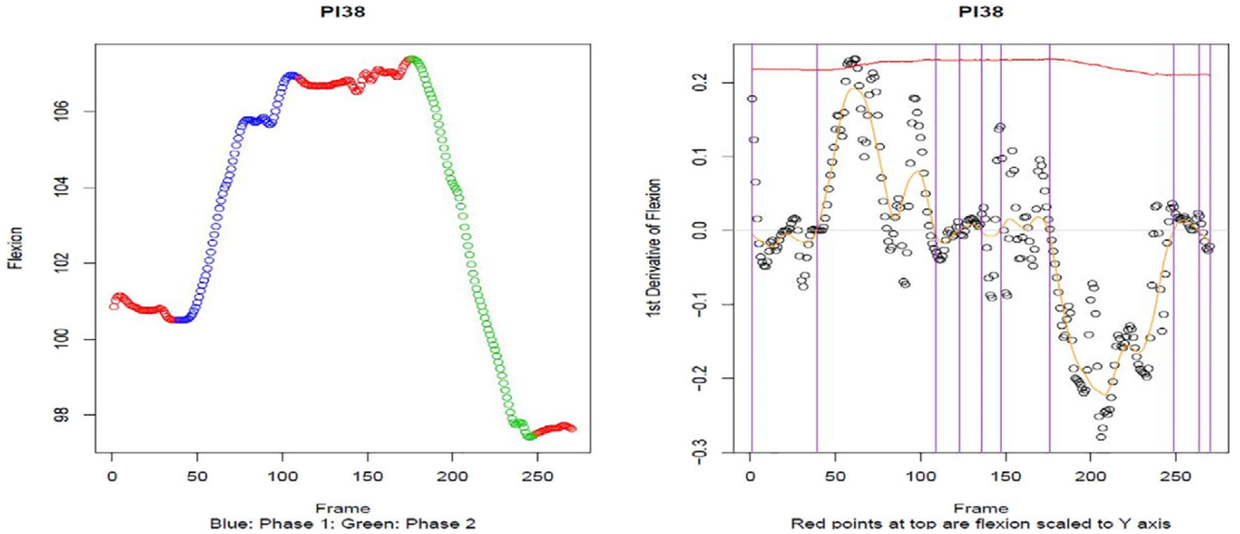


Figure 4. Phase determination for participant 38. Flexion vs fluoroscopy frame was plotted, along with its first derivative. The first derivative plot showed inflexion points, where the derivative curve passed through zero. These inflexion points were used to determine the start and end of the phases.

maxflex, maxflex to 120°, and 120° to 90°. All analyses were completed using IBM SPSS Statistics Version 23 licence 2015 (64-bit edition). Significance was accepted when $p \le 0.05$.

The minimum sample size of four participants in each group was determined using G*Power3 statistical power analysis, which detected a difference between younger (age-range: 20–50) and older (65 ± 9.1 years) age-groups with a power of 95% when using a two sided 5% significance interval calculation [36]. This sample size was derived from the contralateral leg anterior/posterior translation of femoral condyles of younger and older participants for a knee flexed to 90° from Scarvell et al. [37].

3. Results

No differences were found between age-groups for sex, BMI, FCI, or AQoL mental and utility scores. Post-hoc analyses found the 80+ age-group had lower UCLA activity scores, demonstrating that they were less physically active than the younger groups. The AQoL physical score, which measures independent living, pain and the senses, was higher for the 20–39 age-group than both the 60–79 and 80+ age-groups (Table 1).

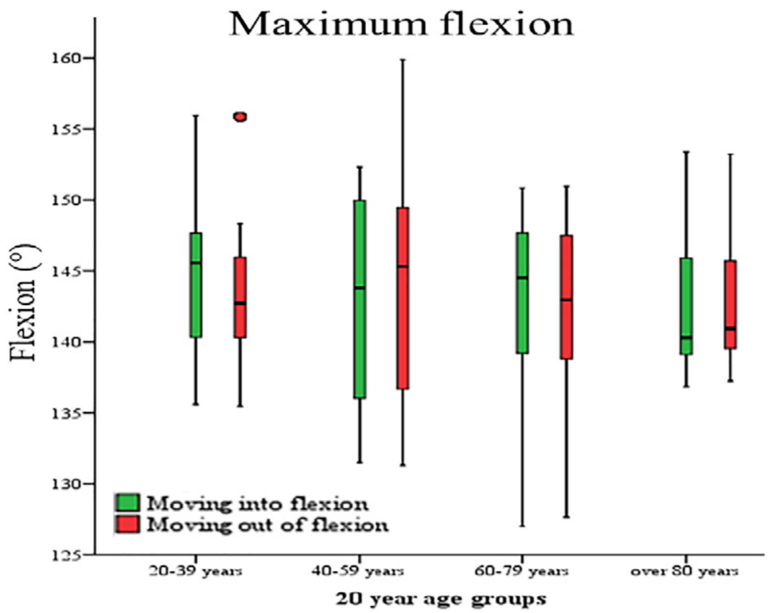


Figure 5. Maximum flexion both into and out of flexion. Unadjusted means for age groups. There were no differences between the groups.

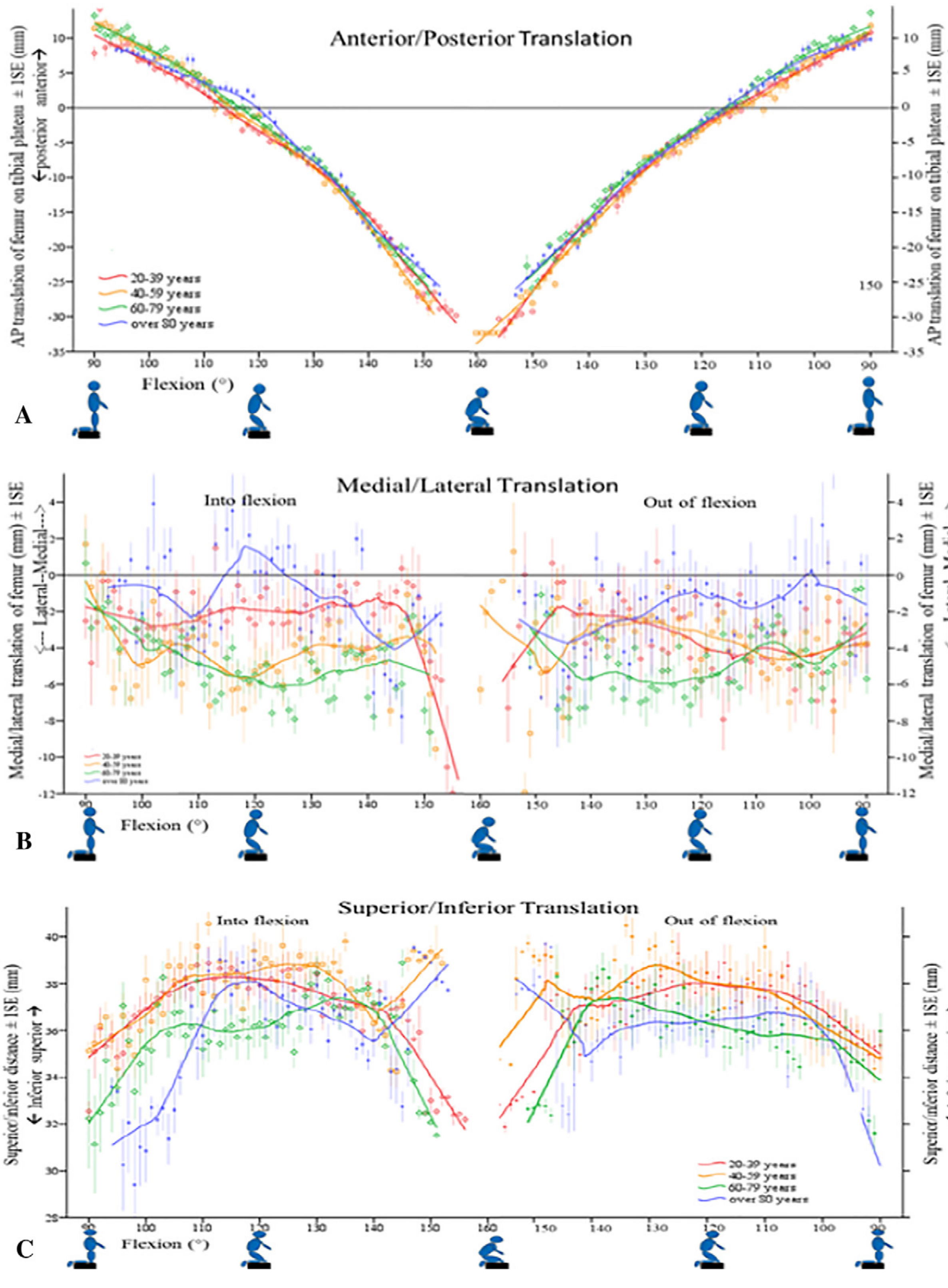


Figure 6. Translation (±1SE) in three planes for the four age-groups. A: anterior/posterior, where at 120° the 80+ age-group were more anterior than the 20–39 age-group, B: medial/lateral, where there were no significant differences, C: superior/inferior, where moving out-of-flexion, the 60–79 age-group slope (rate-of-change) was less than 40–59 age-group.

Table 1
Participant characteristics, Mean (SD).

Age-group (years)	20–39	40–59	60–79	80 +	ρ
N	17	19	23	8	
Age (years)	28.5 (5.9)	51.6 (4.1)	66.6 (5.6)	84.6 (4.0)	
Sex F:M (F%)	7:10 (41%)	10:8 (55%)	16:7 (70%)	3:5 (38%)	0.234
BMI	23.8 (3.3)	25.1 (2.1)	25.4 (4.0)	24.3 (3.0)	0.483
FCI	0.5 (0.8)	0.9 (1.3)	1.4 (2.6)	2.0 (1.9)	0.206
UCLA	9.1 (1.7)	8.6 (1.6)	6.8 (2.7)	5.5 (1.8)	0.000[a]
AQoLD Physical score	0.94 (0.07)	0.90 (0.07)	0.87 (0.10)	0.77 (0.16)	0.003[a]
AQoLD Mental score	0.63 (0.16)	0.57 (0.14)	0.58 (0.15)	0.52 (0.14)	0.389
AQoLD Utility score	0.94 (0.06)	0.92 (0.07)	0.92 (0.06)	0.87 (0.09)	0.102
KL score	0	0	1	0	0.063

[a] Statistically significant; KL: Kellgren-Lawrence score; BMI: Body mass index: FCI: Functional Comorbidity Index; UCLA: University of California, Los Angeles activity score; AQoL: Assessment of Quality of Life score.

Five participants, all in the 60–79 age-group, scored a KL score ≥ 2 and were excluded from the analysis. After their exclusion, there was no difference between the age-groups for the KL median score.

3.1. Knee kinematics

Most kinematic data showed no change; however there were differences at 110° and 120° and over the range 120° to maximum flexion (Table 2, Figure 6 and Figure 7). The adjusted means (or medians for rate-of-change variables) are in Table 3. Results of the Bonferroni post hoc tests are in Table 4.

3.1.1. Flexion/extension

There were no measurable differences between the maximum flexion angles achieved by the four age-groups (Table 3, Figure 5).

3.1.2. Kinematic position

At 110° flexion, 80+ knees were more varus than 20–39 and 40–69 (4.9° (95%CI: 0.6°, 9.1°) and 6.4° (2.1°, 10.7°), respectively) (Table 4 and Figure 7B). At 110° flexion (moving out of flexion), 80+ knees were in a more internal position than 40–69 (9.1° (17.8°, 0.0°) (Table 4 and Figure 7A).

At 120° flexion, the 80+ age-group femur was 5.5 (0.0, 11.0) mm more anterior than 20–39 (Table 4 and Figure 6A).

3.1.3. Kinematic displacement

Between 120° to maximum flexion, 80+ knees rotated into valgus more than 20–39, 40–59 and 60–79 (−5.5° (−9.8°, −1.2°); −5.5° (−9.8°, −1.1°); and −4.5° (−8.0°, −0.9°), respectively) (Table 4 and Figure 7B).

3.1.4. Kinematic rates-of-change (Kruskal–Wallace results)

Between 120° to maximum flexion, the 80+ age-group femurs rotated faster into valgus than the 20–39 age-group, (median: 0.14°/°flex) and (0.04°/°flex), $p = 0.014$ (Table 4 and Figure 7B).

Table 2
One-way MANCOVA group comparison of the linear composite of the position and kinematic displacement variables.

	Into flex					Out of flex				
	Wilks' Λ	F	df	partial η^2	*p*	Wilks' Λ	F	df	partial η^2	*p*
Position										
90°	0.433	0.52	10	0.342	0.842	0.566	0.76	15	0.174	0.716
100°	0.455	0.859	15	0.216	0.611	0.399	1.611	15	0.264	0.097
110°	0.354	2.280	15	0.292	0.010[a]	0.475	1.545	15	0.220	0.111
120°	0.483	1.900	15	0.216	0.033[a]	0.707	0.768	15	0.109	0.709
130°	0.800	0.701	15	0.072	0.780	0.787	0.787	15	0.091	0.690
140°	0.659	0.734	15	0.131	0.741	0.656	0.734	15	0.128	0.741
maxflex	0.737	1.101	15	0.097	0.447	0.787	0.770	15	0.077	0.708
Displacement										
90°–120°	0.145	0.651	10	0.620	0.735					
120°–max	0.395	2.512	15	0.266	0.004[a]					
Max–120°						0.742	0.633	15	0.091	0.833
120°–90°						0.178	1.938	15	0.437	0.055

[a] Statistically significant; these dependent variables are followed up with one-way ANOVA tests, which are then followed up by a Bonferroni test making adjusted pairwise comparisons to determine where the differences lie (Table 4).

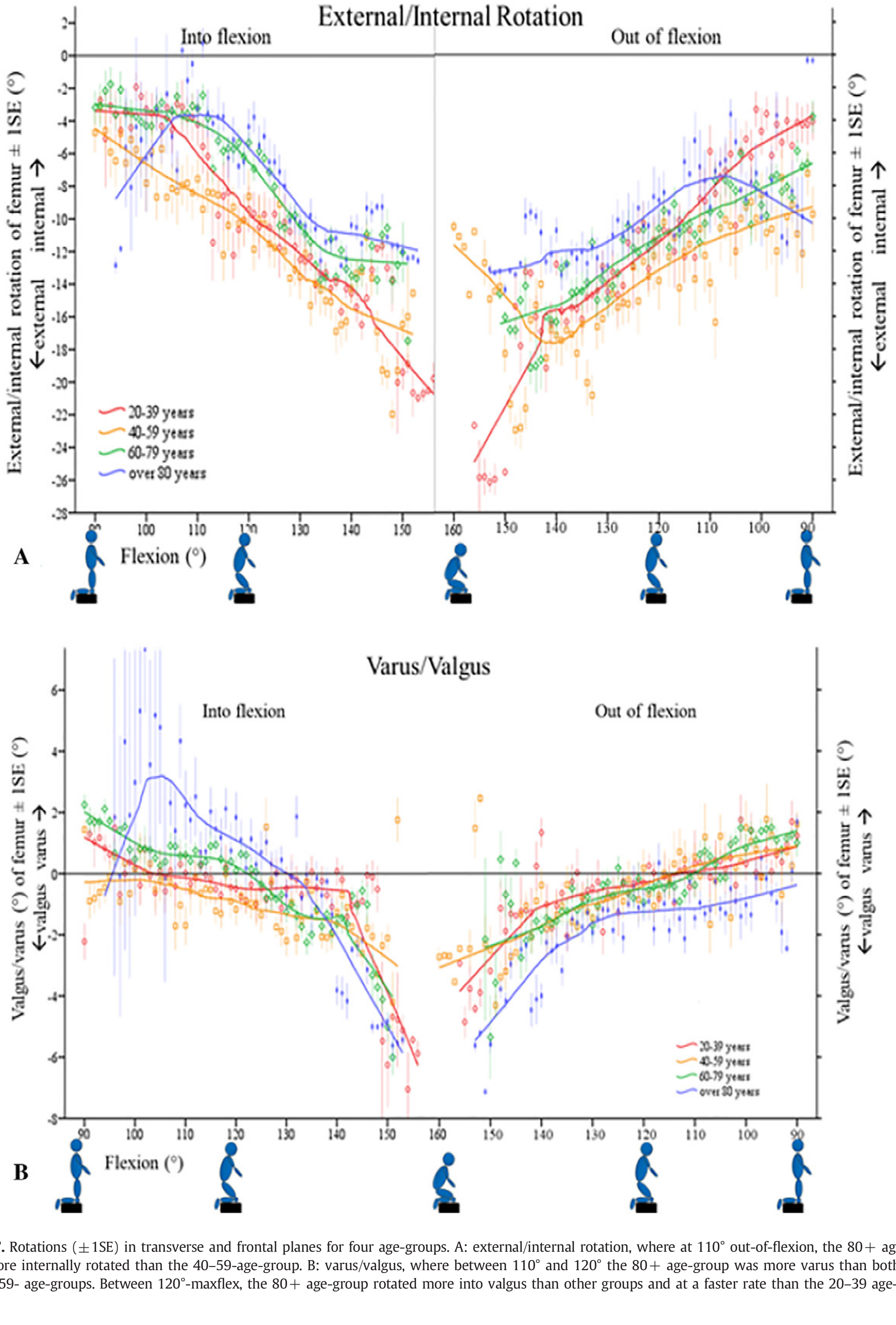


Figure 7. Rotations (±1SE) in transverse and frontal planes for four age-groups. A: external/internal rotation, where at 110° out-of-flexion, the 80+ age-group were more internally rotated than the 40–59-age-group. B: varus/valgus, where between 110° and 120° the 80+ age-group was more varus than both 20–39 and 40–59- age-groups. Between 120°-maxflex, the 80+ age-group rotated more into valgus than other groups and at a faster rate than the 20–39 age-group.

Table 3
Kinematic variables for each age-group. Normative dataset developed with covariates UCLA and AQoL physical score, one-way ANCOVAs.

Age groups[d]	Into flexion									Out of flexion								
	N[c]	20–39	N[c]	40–59	N[c]	60–79	N[c]	80+	ρ	N[c]	20–39	N[c]	40–59	N[c]	60–79	N[c]	80+	ρ
Maximum flexion (°)	16	145.7 (1.6)	18	143.7 (1.4)	22	142.3 (1.3)	9	140.8 (2.3)	0.364	15	144.4 (1.7)	18	145.2 (1.5)	22	141.5 (1.4)	8	141.3 (2.5)	0.336
Anterior/posterior (mm)																		
Position (flex)																		
90°	3	9.4 (2.8)	7	13.2 (1.8)	4	14.1 (2.5)	0		0.461	9	9.9 (1.0)	8	10.9 (1.0)	8	12.2 (1.0)	1	9.7 (3.0)	0.459
100	9	6.4 (2.7)	6	8.0 (4.6)	7	8.5 (3.3)	2	6.1 (1.7)	0.369	8	5.9 (2.1)	5	8.0 (2.6)	14	8.2 (2.9)	5	7.5 (3.6)	0.132
110	9	2.3 (2.8)	7	4.6 (2.4)	13	3.8 (2.9)	5	4.2 (3.0)	0.141	7	1.9 (2.1)	8	1.4 (4.3)	19	3.1 (3.1)	7	2.9 (3.2)	0.079
120°	**14**	**−4.5 (1.0)**	**8**	**−1.4 (1.2)**	**15**	**−1.3 (0.9)**	**7**	**1.0 (1.5)**	**0.038**[a]	10	−3.9 (1.0)	10	−3.6 (0.9)	14	−2.1 (0.8)	7	−0.3 (1.2)	0.190
130°	14	−9.3 (3.5)	12	−9.0 (4.0)	16	−7.6 (2.0)	7	−8.2 (3.3)	0.284	12	−8.8 (1.9)	13	−8.6 (2.9)	16	−7.8 (2.4)	8	−8.3 (3.6)	0.262
140°	14	−16.8 (0.9)	8	−17.2 (1.0)	13	−15.6 (0.8)	6	−15.2 (1.3)	0.592	9	−16.5 (0.9)	9	−17.0 (0.9)	10	−16.2 (0.8)	6	−16.0 (1.2)	0.900
maxflex	16	−21.4 (1.7)	15	−19.4 (1.6)	18	−18.0 (1.5)	8	−16.2 (2.5)	0.406	15	−20.9 (1.7)	15	−19.6 (1.6)	18	−17.6 (1.5)	8	−17.3 (2.5)	0.582
Displacement (mm)																		
90°–120°	3	−13.6 (0.8)	5	−12.1 (0.6)	3	−14.8 (0.8)	0		0.067									
120°–maxflex	14	−17.3 (1.5)	8	−15.8 (1.8)	15	−16.1 (1.4)	7	−16.7 (2.3)	0.906									
Maxflex–120°										10	16.6 (1.6)	9	14.5 (1.6)	14	15.7 (1.3)	7	17.8 (2.1)	0.579
120°–90°										8	13.6 (0.8)	6	13.9 (1.0)	7	14.9 (0.9)	1	11.4 (2.3)	0.534
Rate-of-change (mm/°flex) median[b]																		
90°–120°	15	−0.4	12	−0.4	18	−0.4	6	−0.5	0.679									
120°–maxflex	17	−0.7	16	−0.8	19	−0.8	8	−0.8	0.480									
Maxflex–120°										17	−0.7	16	−0.7	19	−0.7	8	−0.7	0.803
120°–90°										13	−0.4	13	−0.4	19	−0.4	8	−0.5	0.682
Medial/lateral (mm)																		
Position (flex)																		
90°	3	−3.1 (5.6)	7	−0.6 (3.6)	4	−1.2 (5.0)	0		0.928	9	−2.9 (2.4)	8	−4.6 (2.5)	8	−3.5 (2.5)	1	−1.9 (7.1)	0.961
100°	9	−3.1 (5.2)	6	−6.6 (8.9)	7	−1.9 (2.3)	2	−2.8 (4.5)	0.430	8	−3.6 (7.0)	5	−4.4 (4.3)	14	−5.0 (6.2)	5	0.8 (8.9)	0.181
110°	9	−1.8 (5.3)	7	0.7 (6.3)	13	−4.1 (3.4)	5	−3.7 (3.6)	0.294	7	−3.5 (5.2)	8	−2.2 (3.0)	15	−3.5 (3.3)	7	−1.4 (8.0)	0.585
120°	**14**	**−1.4 (1.8)**	**8**	**−5.8 (2.2)**	**15**	**−5.7 (1.6)**	**7**	**2.2 (2.7)**	**0.030**[a]	10	−5.6 1 (2.1)	10	−5.1 (2.0)	14	−5.6 (1.7)	7	−0.7 (2.7)	0.452
130°	14	−1.1 (7.0)	12	−5.2 (7.0)	16	−4.6 (3.3)	7	−2.2 (8.0)	0.284	12	−2.5 (7.5)	13	−2.5 (5.2)	16	−6.9 (6.5)	8	−2.7 (10.3)	0.262
140°	14	−2.4 (1.7)	8	−4.0 (2.1)	13	−4.6 (1.6)	6	−5.2 (2.7)	0.801	9	−0.3 (2.3)	9	−2.9 (2.2)	10	−7.2 (2.1)	6	−4.3 (3.1)	0.208
maxflex	16	−5.0 (1.7)	15	−6.9 (1.5)	18	−9.2 (1.4)	8	−4.5 (2.3)	0.130	15	−4.4 (1.9)	15	−5.5 (1.8)	18	−8.6 (1.6)	8	−3.5 (2.8)	0.214
Displacement (mm)																		
90°–120°	3	1.6 (2.9)	5	1.1 (2.1)	3	−2.9 (2.8)	0		0.509									
120°–maxflex	14	−3.5 (1.5)	8	−0.1 (1.8)	15	2.6 (1.3)	7	−5.8 (2.2)	0.219									
Maxflex–120°										10	0.9 (1.7)	9	1.1 (1.8)	14	1.6 (1.4)	7	1.6 (2.2)	0.756
120°–90°										8	2.1 (2.5)	6	4.0 (2.9)	7	1.4 (2.9)	1	−3.2 (7.0)	0.786
Rate-of-change (mm/°flex) median[b]																		
90°–120°	15	0.0	12	−0.0	18	0.1	6	−0.1	0.449									
120°–maxflex	17	−0.1	16	0.0	19	−0.1	7	−0.1	0.738									
Maxflex–120°										17	0.0	16	0.1	19	−0.1	8	0.0	0.767
120°–90°										13	−0.0	13	−0.0	19	0.0	8	−0.0	0.854
Superior/inferior (mm)																		
Position(flex)																		

(continued on next page)

Table 3 *(continued)*

Age groups[d]	Into flexion									Out of flexion									
	N[c]	20–39	N[c]	40–59	N[c]	60–79	N[c]	80+	ρ	N[c]	20–39	N[c]	40–59	N[c]	60–79	N[c]	80+	ρ
90°	3	34.5 (2.2)	7	35.5 (1.4)	4	31.8 (1.9)	0		0.343	9	35.4 (1.4)	8	34.3 (1.5)	8	33.7 (1.5)	1	28.3 (4.2)	0.450
100°	9	36.4 (2.9)	6	36.9 (4.1)	7	35.3 (5.3)	2	31.4 (3.8)	0.345	8	36.5 (3.2)	5	36.5 (4.4)	18	35.7 (5.5)	5	35.8 (3.3)	0.856
110°	9	37.7 (2.7)	7	38.2 (4.4)	13	37.0 (4.8)	5	35.9 (4.5)	0.834	7	38.2 (3.3)	8	38.2 (4.3)	19	36.6 (5.5)	7	36.8 (3.5)	0.803
120°	14	38.6 (1.2)	8	38.8 (1.4)	15	37.2 (1.1)	7	36.7 (1.8)	0.753	10	38.1 (1.5)	10	38.1 (1.4)	14	37.4 (1.2)	7	36.5 (1.8)	0.917
130°	14	38.2 (2.9)	12	38.8 (3.6)	16	37.5 (3.9)	7	37.8 (3.1)	0.857	12	37.2 (3.6)	13	38.9 (3.7)	20	37.1 (5.1)	8	36.9 (3.7)	0.659
140°	14	37.8 (1.1)	8	37.7 (1.3)	13	36.3 (1.1)	6	34.7 (1.7)	0.549	9	37.4 (1.3)	9	36.8 (1.3)	10	38.1 (1.2)	6	35.7 (1.7)	0.670
maxflex	16	36.0 (1.1)	15	37.1 (1.0)	18	36.0 (1.0)	8	36.4 (1.6)	0.831	15	36.2 (1.1)	15	36.5 (1.0)	18	36.1 (0.9)	8	36.6 (1.6)	0.988
Displacement (mm)																		
90°–120°	3	2.9 (0.6)	5	3.8 (0.4)	3	3.9 (0.6)	0		0.461									
120°–maxflex	14	−2.2 (0.4)	8	−1.6 (0.5)	15	−1.2 (0.4)	7	−0.2 (0.6)	0.104									
Maxflex–120°										10	1.5 (0.5)	9	1.0 (0.5)	14	0.9 (0.4)	7	0.5 (0.6)	0.756
120°–90°										8	−3.3 (0.4)	6	−3.7 (0.5)	7	−4.1 (0.5)	1	−3.3 (1.1)	0.634
Rate-of-change (mm/°flex) median[b]																		
90°–120°	15	0.1	12	0.1	18	0.1	6	0.1	0.442									
120°–maxflex	17	−0.1	16	−0.1	19	−0.1	8	−0.0	0.178									
Maxflex–120°										**17**	**−0.1**	**16**	**−0.1**	**19**	**−0.0**	**8**	**−0.0**	**0.032**[a]
120°–90°										13	0.1	13	0.1	19	0.1	8	0.1	0.221
External/internal (°)																		
Position (flex)																		
90°	3	−7.7 (4.0)	7	−3.8 (2.6)	4	−5.2 (3.6)	0		0.729	9	−5.0 (2.6)	8	−9.6 (2.7)	8	−6.2 (2.6)	1	−0.2 (7.5)	0.505
100°	9	−4.4 (5.7)	6	−6.1 (7.0)	7	−4.6 (4.8)	2	−7.5 (8.8)	0.966	8	−5.6 (6.7)	5	−8.8 (5.4)	18	−9.5 (4.3)	5	−7.7 (7.3)	0.485
110°	9	−4.8 (6.0)	7	−8.2 (5.3)	13	−3.3 (3.4)	5	−3.0 (4.8)	0.225	**7**	**−6.3 (4.4)**	**8**	**−12.4 (4.7)**	**19**	**−10.1 (5.2)**	**7**	**−8.6 (6.7)**	**0.018**[a]
120°	14	−11.2 (2.0)	8	−8.9 (2.4)	15	−5.7 (1.8)	7	−4.0 (3.0)	0.233	10	−13.9 (2.4)	10	−14.9 (2.2)	14	−9.9 (1.9)	7	−8.0 (3.0)	0.289
130°	14	−13.0 (7.7)	12	−13.5 (7.0)	16	−10.7 (4.9)	7	−10.6 (5.5)	0.624	12	−14.8 (6.9)	13	−15.4 (6.0)	20	−13.9 (5.4)	8	−12.4 (6.7)	0.272
140°	14	−15.4 (1.7)	8	−15.7 (2.0)	13	−13.8 (1.6)	6	−9.4 (2.7)	0.320	9	−16.2 (2.2)	9	−16.5 (2.2)	10	−14.8 (2.0)	6	−10.9 (3.0)	0.539
maxflex	16	−16.1 (1.6)	15	−14.7 (1.6)	18	−12.9 (1.4)	8	−11.1 (2.4)	0.413	15	−17.5 (1.7)	15	−16.0 (1.6)	18	−13.4 (1.5)	8	−11.4 (2.5)	0.244
Displacement (°)																		
90°–120°	3	−3.4 (2.2)	5	−4.3 (1.6)	3	−4.2 (2.2)	0		0.949									
120°–maxflex	14	−4.7 (1.6)	8	−2.6 (1.9)	15	−7.0 (1.4)	7	−8.3 (2.3)	0.254									
Maxflex–120°										10	2.6 (1.7)	9	2.3 (1.7)	14	2.9 (1.3)	7	3.0 (2.0)	0.993
120°–90°										8	4.6 (1.0)	6	0.8 (1.2)	7	4.4 (1.2)	1	1.2 (2.9)	0.090
Rate-of-change (°/°flex) median[b]																		
90°–120°	15	−0.0	12	−0.1	18	−0.1	6	−0.1	0.088									
120°–maxflex	17	−0.3	16	−0.2	19	−0.3	8	−0.3	0.620									
Maxflex–120°										17	−0.1	16	−0.2	19	−0.1	8	−0.0	0.890
120°–90°										13	−0.2	13	−0.0	19	−0.2	8	−0.1	0.137
Varus/valgus (°)																		
Position (flex)																		
90°	3	−0.2 (1.7)	7	2.7 (1.1)	4	1.7 (1.5)	0		0.386	9	0.8 (0.6)	8	1.0 (0.6)	8	1.5 (0.6)	1	1.7 (1.7)	0.877
100°	9	0.1 (1.6)	6	0.1 (3.0)	7	0.4 (1.8)	2	1.2 (12.6)	0.485	8	0.1 (2.2)	5	1.6 (3.2)	18	0.8 (2.2)	5	−0.7 (2.0)	0.492
110°	**9**	**−0.1 (2.5)**	**7**	**−1.9 (2.1)**	**13**	**0.4 (1.8)**	**5**	**2.4 (4.3)**	**0.002**[a]	7	1.0 (4.0)	8	−0.03 (1.8)	19	−0.3 (2.9)	7	−1.3 (1.2)	0.838
120°	**14**	**−1.3**	**8**	**−1.6**	**15**	**−0.2**	**7**	**2.8**	**0.010**[a]	10	−0.9	10	−0.2	14	−1.1	7	0.1	0.609

Table 3 *(continued)*

Age groups[d]	Into flexion									Out of flexion								
	N[c]	20–39	N[c]	40–59	N[c]	60–79	N[c]	80+	ρ	N[c]	20–39	N[c]	40–59	N[c]	60–79	N[c]	80+	ρ
		(0.7)		**(0.8)**		**(0.6)**		**(1.0)**			(0.8)		(0.8)		(0.6)		(1.0)	
130°	14	−0.7	12	−1.4	16	−1.2	7	−1.0	0.881	12	−0.1	13	−0.5	20	−1.3	8	−2.1	0.861
		(4.2)		(2.5)		(2.0)		(1.2)			(2.8)		(1.9)		(2.4)		(1.3)	
140°	14	−2.1	8	−0.1	13	−1.1	6	−2.4	0.337	9	−1.2	9	−0.9	10	−1.6	6	−2.9	0.649
		(0.9)		(1.0)		(0.8)		(1.4)			(0.9)		(0.9)		(0.8)		(1.2)	
maxflex	16	−1.8	15	−1.6	18	−1.3	8	−3.0	0.631	15	−1.9	15	−2.2	18	−1.4	8	−2.9	0.629
		(0.8)		(0.8)		(0.7)		(1.2)			(0.8)		(0.7)		(0.7)		(1.1)	
Displacement (°)																		
90°–120°	3	−0.9	5	−3.3	3	−0.8	0		0.359									
		(1.6)		(1.1)		(1.6)												
120°–maxflex	**14**	**−0.3**	**8**	**−0.4**	**15**	**−1.3**	**7**	**−5.8**	**0.004**[a]									
		(0.8)		**(0.9)**		**(0.7)**		**(1.1)**										
Maxflex–120°										10	0.5	9	1.8	14	0.9	7	3.3	0.399
											(1.1)		(1.0)		(0.9)		(1.4)	
120°–90°										8	1.1	6	1.7	7	1.7	1	4.3	0.166
											(0.5)		(0.5)		(0.5)		(1.3)	
Rate-of-change (°/°flex) median[b]																		
90°–120°	**15**	**−0.0**	**12**	**−0.1**	**18**	**−0.0**	**6**	**−0.1**	**0.025**[a]									
120°–maxflex	**17**	**−0.0**	**16**	**−0.0**	**19**	**−0.1**	**8**	**−0.1**	**0.021**[a]									
Maxflex–120°										17	−0.0	16	−0.1	19	−0.1	8	−0.1	0.208
120°–90°										13	−0.1	13	−0.1	19	−0.0	8	−0.0	0.946

[a] Statistically significant results, in bold, that are followed up by an adjusted pairwise comparison.
[b] Rate-of-change values do not have standard error values.
[c] Number of participants with this kinematic data., this changed as participants varied in their start and finish flexion angles.
[d] Estimated marginal means of position(SE), displacement(SE), and median rate-of-change.

4. Discussion

This study measured the kinematics of kneeling in healthy participants aged 20 to 90 years. The most important finding was that age was not related to changes in the kinematics of kneeling in the absence of pain in people under 80. We categorised the participants into four age-groups, 20–39, 40–59, 60–79 and 80+ years, and compared their knee kinematics in six-degrees-of-freedom, throughout a dynamic flexion/extension cycle of kneeling. All age-groups were similar in BMI, FCI, AQoL(mental and utility) scores, and KL scores; but the oldest group was less active with lower UCLA and AQoL physical scores. This study has produced the first normative data set describing healthy kneeling knee kinematics as a function of age.

Age did not diminish maximum flexion. Thus, we can reject our hypothesis that maximum flexion is reduced in the older group and confirm the results of previous motion-analysis studies of squatting and kneeling [26,38]. Maximum flexion depends on posterior femoral translation and external rotation to allow deep flexion without impingement of the femur on the posterior tibial plateau [39]. We found that beyond 120° flexion, posterior-femoral translation, external rotation and maximum flexion were all maintained in the oldest group. The maximum flexion angles reported in this study (144°) support Acker et al., 2011 at 146° whose participants were 46+ years. However, our maximum flexion is less than the 157° reported by Hefzy et al., 1998 for Middle-Eastern males, for whom kneeling was a common activity for prayer. Therefore, the lower maximum flexion seen in our healthy western knees may be a function of lifestyle.

Age did not affect femoral anterior/posterior positions, translations, or rates-of-change (mm/°flex) until 80+ years. Thus, we reject our hypothesis that the femur is more anterior and translates less as we age, except for the 80+ age-group at 120° flexion. One early study investigating ageing knee kinematics found a more anterior tibia in older participants during the stance phase of gait [40]. However, our results do not support this finding during kneeling. Earlier squatting and kneeling studies (using motion-analysis), also found no differences in anterior/posterior translation between younger (23.6 years or < 45 years) and older-age-groups (62.7 years or >45 years) after 120° flexion [26,38]. Strength loss in the quadriceps may explain this difference in the 80+ age-group. At 120° flexion, while kneeling, the quadriceps are highly loaded. If the quadriceps is weak, the participant may increase hip-flexion and lean their torso forward, to assist with managing the increased load. After 120° flexion quadriceps are not required to restrain the descent as they can fall with gravity. However, we did not include electromyograms in our methodology, so we cannot confirm this hypothesis. Recording muscle activation throughout the kneeling cycle would enhance our understanding further.

The femur was not more medial, nor did it have reduced medial/lateral translation during flexion, in the older-age-groups. Likewise, there were no differences in superior/inferior positions and translations. Thus, we reject the hypotheses that an older knee is in a more medial and less superior position and experiences more medial and less superior translation during flexion. This result agrees with Zhou et al. 2012 who found that there were no medial/lateral differences between their age-groups. However, the 60–79 age-group moved faster superiorly than the 40–59 age-group from maxflex to 120° flexion. This difference may be due to the higher maxflex values measured for the older-age-group as shown in the graph.

Table 4
The mean difference between age-groups for the kinematic variables that were shown to be significant, including pairwise contrasts.

Kinematic variable	Age Group 1 (years)	Age group 2 (years)	Mean difference (age gp1 − age gp2) mean(95%CI)	*Adjusted Significance *p*
Anterior/posterior (mm)				
Position (flex)				
120° into flexion	**20–39**	40–59	−3.1 (−7.3, 1.1)	0.276
		60–79	−3.2 (−7.2, 0.7)	0.172
		80+	**−5.5 (−11.0, −0.0)**	**0.048***
	40–59	60–79	−0.1 (−4.3, 4.1)	1.000
		80+	−2.4 (−7.9, 3.2)	1.000
	60–79	80+	−2.3 (−6.8, 2.3)	1.000
Medial/lateral (mm)				
Position (flex)				
120°into flexion	20–39	40–59	4.4 (−3.2, 12.1)	0.691
		60–79	4.3 (−2.9, 11.6)	0.631
		80+	−3.6 (−13.6, 6.5)	1.000
	40–59	60–79	−0.1 (−7.8, 7.6)	1.000
		80+	−8.0 (−18.2, 2.2)	0.208
	60–79	80+	−7.9 (−16.2, 0.5)	0.075
Superior/inferior (mm)				
Rate-of-change (flexion range) #				
Maxflex–120°	20–39	40–59	#	1.000
		60–79	#	0.629
		80+	#	1.000
	40–59	**60–79**	**#**	**0.023***
		80+	#	0.584
	60–79	80+	#	1.000
External/internal (°)				
Position (flex)				
110° out-of-flexion	20–39	40–59	6.4 (0.1, −0.8))	0.105
		60–79	0.4 (1.0, −6.4))	1.000
		80+	−2.8 (1.0, −11.4)	1.000
	40–59	60–79	−6.0 (0.1, -12.5)	0.089
		80+	**−9.1 (0.0, −17.8)**	**0.034***
	60–79	80+	−3.2 (1.0, −10.1)	1.000
Varus/valgus (°)				
Position (flex)				
110° into flexion	**20–39**	40–59	1.6 (−1.7, 4.8)	1.000
		60–79	−1.7 (−4.8, 1.4)	0.801
		80+	**−4.9 (−9.1, −0.6)**	**0.017***
	40–59	**60–79**	**−3.2 (−6.4, −0.1)**	**0.042***
		80+	**−6.4 (−10.7,- 2.1)**	**0.001***
	60–79	80+	−3.2 (−6.8,0.4))	0.109
Displacement (flex range)				
120°–maxflex	**20–39**	40–59	0.0 (−3.2,3.3)	1.000
		60–79	1.0 (−2.1,4.1)	1.000
		80+	**5.5 (1.2,9.8)**	**0.006***
	40–59	60–79	1.0 (−2.3,4.2)	1.000
		80+	**5.5 (1.1,9.8)**	**0.007***
	60–79	**80+**	**4.5 (0.9,8.0)**	**0.007***
Rate-of-change (flexion range) #				
90°–120°	20–39	40–59	#	0.051
		60–79	#	1.000
		80+	#	0.364
	40–59	60–79	#	0.156
		80+	#	1.000
	60–79	80+	#	0.768
120°–maxflex	**20–39**	40–59	#	1.000
		60–79	#	1.000
		80+	**#**	**0.014***
	40–59	60–79	#	1.000
		80+	#	0.067
	60–79	80+	#	0.206

Statistically significant (in bold), $\rho < 0.05$, with Bonferroni adjustments made for multiple comparisons; #Kruskal–Wallis test where the mean difference is not reported.

In contrast, Zhou et al. found no significant difference in superior/inferior translation over this flexion range between their groups and thus no difference in rate-of-change. There are two potential explanations for this discrepancy. First, the Kruskal-Wallis test did not consider covariates, and second, the magnitude of the data is small and may be within the margin of error for the measurement. This data will require further confirmation.

No differences in external/internal angles, rotations and rates-of-change were found between any of the age-groups with only one exception at 110°. This outcome supports two previous motion-analysis studies; Yuhara et al. [41] found no difference during squatting between 67.7(SD:1.4) and 73.1(3.3)-year-old groups, and Zhou et al. found no differences during kneeling between 23.8 (1.6) and 60.4(2.5)-year-old groups. Moro-oka et al. used CT-fluoroscopy 3D/2D registration with a younger age-group (mean 29 years). Our reported external/internal angle at 120° flexion of 11.2° (2.0°) agreed with their 10.8° (1.9°). This agreement remains at 140° flexion with 15.4° (1.7°) compared to 16.8° (1.9°) at 135° flexion, thus demonstrating good external validity.

We hypothesised that the older-age-groups would have increased knee varus angles and more varus rotation during flexion. This hypothesis was not met, except for the 80+ age-group at 110°, and between 120° to maximum flexion. At 110° flexion, the oldest group had a larger knee varus angle than the 20- 39 and the 40- 59 age groups. This exaggerated varus position and rotation may be associated with the anterior position of their femur at this flexion angle [39]. By referring to the shape of the tibial plateau and its effect upon the motion of the medial and lateral femoral condyles, an explanation of this motion can be proposed [39]. At 100°–110° flexion the more anterior lateral femoral condyle could be raised because of the convex shape of the lateral tibial plateau, while the medial femoral condyle is still confined to the cupola and is lower on the medial tibial plateau. Thus, a lower medial femoral condyle and a raised lateral femoral condyle can result in a femoral varus position. Between 120° and maximum flexion, the 80+ femurs rotated into valgus more than other age-groups. This increased rotation could be due to the shape of the posterior 'gutter' of the lateral tibial condyle, down which the lateral femoral condyle could move, as it translates posteriorly from a more anterior position [39]. Future studies that included the motion of the medial and lateral femoral condyles on the tibial plateau would help explain this difference.

No previous studies have used 3D/2D registration measurement technology to investigate kneeling kinematics in ranges over 120° flexion in six-degrees-of-freedom [10]. Using motion-analysis with skin-markers, one previous study examined kneeling in six-degrees-of-freedom and found no effect due to ageing [26]. Another study that investigated kneeling kinematics which used 3D/2D registration technology only reported anterior/posterior translation and internal/external rotation [22]. Overall, our data confirm the findings of a meta-analysis that investigated healthy-knee-kinematics in deep flexion. That analysis found that despite different measurement technologies and reference systems, the medial and lateral femoral condyles moved posteriorly on the tibial plateau during deep flexion after 120° [10].

This study has several limitations. First, there is an increased error in varus/valgus and mediolateral translation compared to the other kinematic variables because they were out of plane. Second, G&S mediolateral and superior/inferior kinematics are potentially altered when varus/valgus ≠ 0°. Third, we did not include measurements from a force plate nor electromyography. Finally, our 80+ year group had the least number of participants.

We have now developed a description of knee kinematics over a full cycle of kneeling in six-degrees-of-freedom across four age-groups and reported the effects of ageing on kinematics. Into flexion, the femur moves posteriorly, remains lateral, moves away from (superiorly) and then back to (inferiorly) the tibial plateau, while externally rotating and moving into valgus. Out-of-flexion kinematics of the four age-groups was very similar.

In conclusion, this study has produced a normative kneeling data-set from which clinicians may assess kinematic changes and measure the effectiveness of treatments in returning knee kinematics to a healthy state. Clinical decision making for knee pain includes the consideration of risk factors. Ageing has been described as a non-modifiable risk factor for knee osteoarthritis, with increasing risk up to the age of 80 [11,42–44]. However, in the absence of osteoarthritis, older knees should be considered to be normal and treated in the same way as younger knees. Kneeling is a difficult activity for people with osteoarthritis but difficulty kneeling should not be considered to be an inevitable consequence of ageing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.knee.2019.07.012.

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