Radiographic analysis in Thoroughbreds reveals morphological changes in healthy maturing stifle joints and possible association between subchondral lesions and femoral condyle width

Laure Wadbled, DVM, MSc¹,²; Cyrielle Finck, DVM, DVSc, DACVR¹*; Elizabeth M. Santschi, DVM, DACVS³; James P. Morehead, DVM⁴; Ursula Fogarty, MVB, PhD⁵; Thibaut Lemirre, DVM, MSc¹,²; Guy Beauchamp, PhD³; Hélène Richard¹,²; Sheila Laverty, MVB, DACVS, DECVS¹,²

¹Département de Sciences Cliniques, Faculté de Médecine Vétérinaire, Université de Montréal, St-Hyacinthe, Québec, Canada
²Comparative Orthopaedic Research Laboratory, Département de Sciences Cliniques, Faculté de Médecine Vétérinaire, Université de Montréal, St-Hyacinthe, Quebec, Canada
³Department of Clinical Sciences, College of Veterinary Medicine, Kansas State University, Manhattan, AR
⁴Equine Medical Associates, Lexington, KY
⁵Irish Equine Centre, Johnstown, County Kildare, Ireland

*Corresponding author: Dr. Finck (cyrielle.finck@umontreal.ca)

OBJECTIVE
Assess femorotibial features in foals with and without medial femoral condyle (MFC) subchondral radioluencies (SR+ and SR–).

METHODS
3 independent, sequential radiographic studies were performed. Study 1 retrospectively measured femorotibial morphological parameters in repository radiographs (SR– and SR+). Study 2 qualitatively compared drawings of intercondylar notch shape in postmortem radiographs (SR–). Study 3 prospectively measured femorotibial parameters in 1-month-old foals (SR–). In studies 1 and 3, 13 morphologic parameters were measured. Limb directional asymmetry was assessed in 2 age groups (< 7 or ≥ 7 months).

RESULTS
Study 1 (SR– group; n = 183 radiographs) showed increased femoral measurements with maturation, except the distal femoral intercondylar notch width (FINw), which decreased. In contrast, in SR+ stifles (53 radiographs), 3 femoral parameters (MFC width [MFCwpf], MFC height, or FINw) showed no changes. Tibial plateau width alone increased with maturation in both groups. Interobserver reliability was good to excellent. Study 2 (n = 53 radiographs) confirmed a distal FINw decrease in SR– foals. In study 1, left SR– stifles in greater than or equal to 7-month-old fillies had significantly larger femoral bicondylar width and FINw, while right SR+ stifles in fillies greater than or equal to 7 months had a significantly larger MFCw. In study 3 of 1-month-old foals (n = 94 SR– radiographs), the MFCw, femoral condyle bicondylar width, and lateral femoral condyle height were all greater on the left, whereas the intercondylar intereminence space width was larger on the right.

CLINICAL RELEVANCE
In SR+ stifles, the distal femur exhibited divergent maturation, indicating a wider MFC in the right stifle in older foals. As SR lesions are more common on the right, this suggests a potential association with MFC morphology.

Keywords: horse, stifle, subchondral radioluencies, radiography, morphology
lameness, and require costly medical and surgical interventions to alleviate discomfort.²

A recent microCT (μCT) study¹ of a cohort of Thoroughbred foals postmortem detected SR lesions in 19% of the foals from 5 weeks of age onward. The initial lesions were axial transitioning to solely central beyond 7 months of age. These findings agree with prior radiographic studies.²⁻⁴ This time point also coincides with the timeframe of completion of endochondral ossification, a marker of maturation of the articular epiphyseal cartilage complex of the MFC.⁵

The precise etiology of SR remains uncertain. The results of the study¹ employing μCT and histology of juvenile Thoroughbred MFCs lend support to the notion of focal trauma occurring at the joint surface as a contributing factor as separation or fracture at the osteochondral junction was observed in some specimens. Other experimental surgical models of focal trauma to the MFC in adult horses have also confirmed that trauma can induce cyst development in mature horses.⁵,⁶ On the other hand, osteochondrosis, a focal defect of endochondral ossification, resulting from ischemic chondronecrosis of the vascular growth plate of the epiphysis, has also been proposed as a cause of SR.¹⁰,¹¹

The biomechanical forces within the developing stifle joint likely undergo modifications with growth and maturation. The forces conveyed through the stifle joint are influenced by its arthrokinematics, determined by the shape, menisci, and soft tissues of the bones.¹² Imaging studies¹³,¹⁴ of the morphological maturation of healthy human distal femurs have found that the shape of the intercondylar notch evolves from an early A shape in children to a later omega shape (Ω) in young adults. A narrow configuration of the femoral intercondylar notch or a low notch width index (NWI) is a recognized risk factor for the development of MFC osteochondritis dissecans (OCD) in people.¹⁵ The NWI is a ratio between the width of the femoral intercondylar space and its bicondylar width, measured on anteroposterior radiographs. The diminished NWI in knees with MFC OCD lesions is believed to create tibial eminence impingement and microtrauma contributing to the development of lesions.¹⁵ Furthermore, stenosis or narrowing of the intercondylar notch has been linked to anterior cruciate ligament rupture in children,¹⁶,¹⁷ adults,¹⁸,¹⁹ and dogs.²⁰ Taken together, these studies suggest that the interplay of dynamic maturation-related morphological and kinematic changes in the stifle joint could exert an impact on stifle injuries in both juvenile humans and animals. Although not yet explored in young horses, stifle arthrokinematics may also change with the musculoskeletal development of joint disease, but none has yet measured changes in shape with maturation and association with the development of lesions.

Of interest to the current investigation, there is also a notably higher prevalence MFC SR in the right limb spanning from 64% to 90%,²⁻³,⁶,⁷ which could potentially be linked to asymmetries in bone shape affecting stifle arthrokinematics. Discrepancies have been noted in directional limb asymmetry, defined as a significant difference between left and right limb long bone width and length, in people from birth onward.²⁸ Hindlimb asymmetries have also been documented in adult horses, as femoral diaphyseal width and metatarsal III length are all greater in the right hindlimb but have not been studied in juveniles.²⁹,³⁰

The aim of this investigation was to study morphological changes and limb directional asymmetry in the femur or tibia during maturation in the developing stifle of healthy Thoroughbreds and identify differences in foals with MFC SR that could contribute to their genesis.

**Methods**

Three consecutive investigations were conducted (referred to as studies 1 to 3). Following the completion of study 1, studies 2 and 3 were subsequently designed to provide further validation for specific findings obtained in the initial study 1.

**Study 1: retrospective radiographic analysis of juvenile Thoroughbreds (aged 3 to 23 months) to measure morphological parameters of the distal femur and proximal tibia**

Bilateral stifle radiographs from a cohort of juvenile Thoroughbreds were retrieved from a radiograph repository that was originally created to identify skeletal pathology in preparation for yearling sales as previously reported.² A subset of individuals within this cohort had also been radiographed on 3 occasions (T1, 6 months; T2, 12 months; and T3, 18 months of age). This design increased the sample size available for exploring changes at different ages. The radiographs were procured in the field by equine veterinarians from 1 practice using digital radiography (NEXT Equine DR; Sound Imaging). The caudo-15°-proximal–craniodistal (Cd15Pr-CrDi) stifle radiographic views were retrieved for examination for the current study.

**Quality control step**—An initial quality control step of each radiograph was made by a board-certified veterinary radiologist (CF) to ascertain whether it would permit an accurate measurement of the selected radiographic parameters. Exclusion criteria were instances of rotation, inadequate centering, and motion blurring. Radiographs deemed to be of insufficient quality for the purposes of morphological measurement were excluded before analysis. The selected stifle radiographs were then screened for MFC lesions and categorized into 2 distinct stifle groups: stifle radiograph MFC with no SR (SR−) and stifle radiograph MFC with SR (SR+) to allow comparisons between both (Supplementary Figure S1).
Morphological features assessed—All measurements were performed employing Horos software (Horosproject.org; Nimble Co LLC d/b/a Purview; version 3.1.0). The choice of the anatomical parameters of interest was informed by previous research\(^1\) and conducted on the human knee for similar objectives or developed de novo. A total of 13 parameters were measured (Figure 1).

Distal femur morphological parameters—Width of the lateral and medial femoral condyles (LFCw and MFCw, respectively), bicondylar width (FCw), width of the femoral intercondylar notch (FINw), and height of the lateral and medial condyles (LFCh and MFCh, respectively) (Figure 1) were all measured. All femoral width measurements were made at 2 predetermined levels, as described previously.\(^1\) This approach was adopted to account for heterogeneity in the intercondylar notch shape that could cause differences in measurements from proximal to distal. The first level was at the popliteal fossa (pf), defined as a line extending through it and parallel to a line through the distal extremities of both femoral condyles. The second level was the articular line (al) adapted from an MRI investigation of human knee parameters\(^1\) and defined as a line parallel to a reference line passing through the most distal parts of the femoral condyles, situated at the most distal and narrow aspect of the femoral intercondylar notch (Supplementary Figure S2). If the pf was not

---

**Figure 1**—Illustration of stifle morphological parameters measured on caudo-15\(^\circ\)-proximal–craniodistal radiographs. All femoral width measurements were taken at 2 levels, at the popliteal fossa (pf) (when visible) and the articular line (al), because of the variability in intercondylar notch shape from proximal to distal. Further details on the definition of the al are provided (Supplementary Figure S2). The measurement sites are illustrated by blue arrows. The arrows are not superposed for illustrative purposes alone (the measurements were made at the same level). A—Lateral femoral condyle height (LFCh) and medial femoral condyle height (MFCh) were measured from the physis to the al. B—Condyle width measurements taken at the level of the pf: bicondylar (FCwpf), lateral femoral condyle (LFCwpf), and medial femoral condyle (MFCwpf) widths. C—Condyle width measurements taken at the level of the al: bicondylar (FCwal), lateral femoral condyle (LFCwal), and medial femoral condyle (MFCwal) widths. D—Intercondylar notch width (FINw) measurements at the pf and al. E—Tibial plateau width (TPw), medial intercondylar eminence height (MICETH), and intercondylar intereminence space width (ICIESw). Broken black line indicates lateral intercondylar eminence.
clearly visible, no measurements were made (data not available for analysis).

**Proximal tibia morphological parameters**—The tibial plateau width (TPw), medial intercondylar eminence height (MICEth), and intercondylar eminence space width (ICIESw) were measured (Figure 1). The TPw was measured at the widest part of the tibial plateau between the junctions of the articular surface with the lateral and medial cortices (tibial plateau line). The MICEth was defined as the distance from the tibial plateau line to the summit of the medial eminence. The ICIESw was measured between 2 lines that bisected each medial and lateral eminence and were perpendicular to the tibial plateau line.

**Interobserver reliability assessment**—Radiographic measurements were performed on an initial subset of 10 SR− radiographs from study 1, independently by the 2 readers (a DACVR and a veterinarian), blinded to patient information, who had previously familiarized themselves with the measurements in an initial training session. The interreader reliability was assessed using an intraclass correlation coefficient (ICC).

**Study 2: retrospective analysis of radiographs from a repository of postmortem distal femurs (aged 2 weeks to 19 months) to qualitatively evaluate differences in femoral intercondylar notch shape between 2 groups of ages**

Building on the outcomes of study 1, this study was designed to visually depict the development of the intercondylar notch. For this purpose, postmortem Cd15Pr-CrDi radiographs of the distal femur alone (without soft tissues and tibia) that were available in a repository from a prior investigation7 (Supplementary Figure S3) were retrieved.

It was determined that these available radiographs of the bone, without the tibia and soft tissue attachments, would permit a more accurate tracing and depiction of the femoral intercondylar notch to illustrate shape changes with age. In total, 110 femurs had been collected. Two subsets of radiographs (foals aged 1 to 2 months and weanlings aged 6.5 to 9 months) were extracted for comparative purposes (Supplementary Figure S4). They were chosen to contrast changes between the youngest foals with those that were most mature. The shape of the intercondylar notch of each limb was drawn on the digitalized radiographs using Paint.NET 4.2.16, and the drawings were extracted, aligned, and qualitatively compared. As the shape assessment was a subjective estimation, it was performed by 1 observer.

**Study 3: a prospective examination of a cohort of thoroughbred foals (aged 1 month) to measure early postpartum morphological parameters of the distal femur and proximal tibia**

This prospective study was then designed to determine whether the limb directional asymmetry that was observed in study 1 was present in very young foals and therefore potentially already present at birth. Bilateral standardized Cd15Pr-CrDi stifle radiographic views were taken by the same veterinary practice, with the owners’ consent (Supplementary Figure S5). Before the study, an image of the ideal radiographic view suitable for the current investigation was first sent to the veterinarians, in an attempt to better standardize the views to permit the most accurate measurement of the same morphological parameters that were refined for study 1 (Supplementary Figure S6). A quality control step was also performed before making the measurements.

**Statistical analysis**

A statistical analysis was performed on data from studies 1 and 3.

**Study 1**—For the analysis of the SR− group, measurements from bilateral, lesion-free stifles were included. For the SR+ group analysis, measurements of all radiographs with a lesion in the right and left stiffe were included. The radiographs of any contralateral lesion-free stifle were excluded from all the analyses. Both groups (SR− and SR+) were subcategorized into 2 age groups of less than 7 months and greater than or equal to 7 months old for comparative purposes. The 7-month cut-off was selected as endochondral ossification, a marker of maturation, is completed in the equine MFC at 7 months.7

**Changes with maturation**—A mixed linear model, with the subject as a random effect and the gender (male, female), side, and age as fixed effects, was employed to interrogate the changes in morphological parameters with maturation in the SR+ and SR− groups separately.

**Directional asymmetry of morphological features between limbs (studies 1 and 3)**—Limb directional asymmetry refers to the phenomenon whereby morphological features exhibit a measurable, consistently significant difference between a pair of limbs. Directional asymmetry (%) was calculated in the age subgroups for each measured parameter as follows: directional asymmetry (%) = (R/L)/(average of R and L) X 100,31 as described in previous human studies, where R is right and L is left.26,32

The effects of this age category and side (right and left) for directional asymmetry were then analyzed. The limb directional analysis was also performed on the stifle radiographic parameters from study 3 in 1-month-old foals to also determine the presence of directional asymmetry in this younger population.

A Benjamin-Hochberg sequential adjustment was performed to interrogate the interaction between sex, age, and side. The normality of the residual values for each model was evaluated with quantile-quantile plots. Each model was applied to each SR group, for a total of 26 models. Many, but not all, of the dependent measures (TPw, MICEth and ICIESw) are strongly correlated. Thus, although the results for each measure are presented separately,
similar effects of age, side, or sex are expected for correlated variables.

The statistical analyses were performed by a certified statistician (GB) using statistical software (R v. 4.1.1.; The R Foundation), and the level of statistical significance was set at $P < .05$. Unless otherwise stated, results are presented as the following: $P$ value and least-square means ± SE.

**Results**

**Interobserver reliability**

The ICC values for the assessed morphological characteristics varied across a range from 70.4 (FINwpl) to 99.8 (TPw) (Table 1). The ICC values over 60% were considered good and above or equal to 90% were considered excellent.33

<table>
<thead>
<tr>
<th>Intraclass coefficient correlation (ICC) for both observers for the stifle (n=10) radiographic morphological parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interrater ICC (%)</strong></td>
</tr>
<tr>
<td>Femur</td>
</tr>
<tr>
<td>MFCwal</td>
</tr>
<tr>
<td>LFCwpf</td>
</tr>
<tr>
<td>LFCwal</td>
</tr>
<tr>
<td>FCwpf</td>
</tr>
<tr>
<td>FCwal</td>
</tr>
<tr>
<td>MCh</td>
</tr>
<tr>
<td>LCh</td>
</tr>
<tr>
<td>FINwpl</td>
</tr>
<tr>
<td>FINwpl</td>
</tr>
<tr>
<td>Tibia</td>
</tr>
<tr>
<td>MICETh</td>
</tr>
<tr>
<td>TPw</td>
</tr>
</tbody>
</table>

al = Articular line. FCw = Bicondylar width. FINw = Femoral intercondylar notch width. ICIESw = Intercondylar interemience space width. LFCw = Lateral femoral condyle height. LFCw = Lateral femoral condyle width. MFCw = Medial femoral condyle width. MCh = Medial femoral condyle height. MFCw = Medial femoral condyle width. MICETh = Medial intercondylar eminence height. pf = Popliteal fossa. TPw = Tibial plateau width.

**Study 1: retrospective analysis of stifle radiographs (SR+ and SR−)**

A total of 392 Cd15Pr-CrDi radiographs (from 78 horses and 156 stifles) were retrieved and evaluated in the quality control step.

Of these, a total of 236 radiographs (from 78 horses and 118 stifles) were judged to be suitable for the measurements of the morphological features (Supplementary Figure S1). Within this final cohort, a subgroup of 14 horses had radiographs taken at T1 alone, 27 at T1 and T2, and 30 on all 3 occasions (T1 to T3).

The pf was not clearly visible in 35 radiographs so the measurements at this specific site were not made.

**SR− group analysis: MFC lesion-free joints**

A total of 183/236 (77.5%) radiographs (from 56/78 horses and 87/118 stifles, with 27 females and 29 males) were categorized as SR−, with 85/183 (46.4%) radiographs in the less than 7-month-old category and 98/183 radiographs (53.6%) in greater than or equal to 7-month-old category. A complete data set for all the morphological parameters measured is provided (Table 2).

**Morphological changes with maturation and sex**

For the femur, there was a significant increase ($P < .0001$) in all condylar width and height measurements with age (Figure 2). The FINwal, MFCwal, and ICIESw significantly changed from 70.4 (age 7 months) to 99.8 (age 7 months old) in males and females. No significant difference was noted between the right and left limbs. The left FINwal, MFCwal, and ICIESw did not change (Figure 2). The TPw was greater in male horses in both age groups ($P < .01$).

**Directional asymmetry**—In the less than 7-month-old age group, the left FINwal was significantly larger ($P < .04$). In the greater or equal to 7-month-old group, both FCw and FINw were significantly larger in the left limbs, compared with right limbs, at both levels (FCwal, $P < .04$; FINwal, $P < .03$; FINwal, $P < .04$; FINwal, $P < .02$; FINwal, $P < .03$) in male horses in both age groups.

For the tibia, TPw significantly increased ($P < .0001$) with maturation but the MICETh and the ICIESw did not change (Figure 2). The TPw was greater in male horses in both age groups ($P < .01$).

**SR+ group: MFC lesions**—A total of 53/236 (22.5%) radiographs from 21/78 horses (28%), 11 females and 10 males, and 31/118 (26.3%) stifles were categorized as SR+. A total of 19/53 (35.8%) radiographs were in the less than 7-month-old category, and 34/53 (64.2%) radiographs were in the greater than or equal to 7 months old. Of these, 8 were unilaterally affected (all right sided) and 7 bilaterally.

**Morphological changes with maturation and sex**

For the femur, there was a significant increase in FCw (FCwal, $P < .003$; FCwal, $P < .0001$), MFCw (MFCwal, $P < .0006$), LFCw (LFCwal, $P < .0004$; LFCwal, $P < .001$), and LCh (LCh $< .0001$) measurements with maturation. However, unlike SR−, no significant differences were observed for MFCwal, MCh, or FINwal. Many femoral parameters were significantly larger in males. These included FCwal, $P < .02$; FCwal, $P < .006$; MFCwal, $P < .04$; LFCwal, $P < .02$; MCh, $P < .03$; LCh, $P < .04$; FINwal, $P < .007$.

For the tibia, similar to the SR− group, TPw significantly increased ($P < .0001$) with maturation but not the MICETh or the ICIESw measurements. The TPw and the MICETh were also significantly larger in males ($P < .01$ and $P < .008$, respectively).

**Directional limb asymmetry**—The pattern of asymmetry was different from that observed in the SR− group (Supplementary Figure S7). The MFCwal alone was significantly larger on the right in females older than or equal to 7 months ($P < .004$). The magnitude of the difference between the right and left sides of the females was an average of 1.8 mm for the less than 7-month-old group but an average...
Table 2—Study 1: radiographic morphological measurements of the left and the right stifle of both groups [SR− and SR+], subcategorized into 2 age groups (< 7 months old and ≥ 7 months old), and data (mean of right and left stifle measurements at all ages) of the SR− and SR+ groups subdivided into 2 sex groups (male/female).

<table>
<thead>
<tr>
<th></th>
<th>&lt; 7 months old</th>
<th>≥ 7 months old</th>
<th></th>
<th>&lt; 7 months old</th>
<th>≥ 7 months old</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right stifle</td>
<td>Left stifle</td>
<td></td>
<td>Right stifle</td>
<td>Left stifle</td>
</tr>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>P value</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>MFCwpf</td>
<td>44.7 (3.22)</td>
<td>43.7 (3.68)</td>
<td>.28</td>
<td>46.65 (2.93)</td>
<td>46.68 (3.36)</td>
</tr>
<tr>
<td>MFCwal</td>
<td>46.74 (3.22)</td>
<td>46.86 (3.52)</td>
<td>.06</td>
<td>49.87 (3.17)</td>
<td>49.81 (3.15)</td>
</tr>
<tr>
<td>LFCwpf</td>
<td>47.03 (2.89)</td>
<td>47.33 (2.96)</td>
<td>.56</td>
<td>49.39 (3.73)</td>
<td>50.44 (3.6)</td>
</tr>
<tr>
<td>LFCwal</td>
<td>50.32 (3.18)</td>
<td>49.97 (3.38)</td>
<td>.57</td>
<td>52.82 (3.54)</td>
<td>53.84 (2.71)</td>
</tr>
<tr>
<td>FCwpf</td>
<td>120.36 (5.88)</td>
<td>120.07 (5.73)</td>
<td>.53</td>
<td>122.72 (6.08)</td>
<td>125.76 (6.15)</td>
</tr>
<tr>
<td>FCwal</td>
<td>120.01 (6.44)</td>
<td>119.68 (6.65)</td>
<td>.58</td>
<td>123.57 (6.33)</td>
<td>126.17 (5.29)</td>
</tr>
<tr>
<td>MFC</td>
<td>66.96 (4.65)</td>
<td>66.80 (4.80)</td>
<td>.38</td>
<td>70.56 (3.59)</td>
<td>70.58 (3.22)</td>
</tr>
<tr>
<td>LFCh</td>
<td>67.73 (4.28)</td>
<td>65.18 (4.41)</td>
<td>.29</td>
<td>72.65 (3.61)</td>
<td>73.28 (3.24)</td>
</tr>
<tr>
<td>FINwpf</td>
<td>27.89 (2.54)</td>
<td>28.92 (2.59)</td>
<td>.1</td>
<td>26.52 (2.27)</td>
<td>28.2 (2.75)</td>
</tr>
<tr>
<td>FINwal</td>
<td>21.44 (2.71)</td>
<td>23.03 (4.96)</td>
<td>.04*</td>
<td>20.2 (2.4)</td>
<td>21.82 (2.76)</td>
</tr>
<tr>
<td>ICIESw</td>
<td>16.29 (2.36)</td>
<td>15.80 (1.73)</td>
<td>.12</td>
<td>15.3 (1.65)</td>
<td>15.73 (1.73)</td>
</tr>
<tr>
<td>MICETh</td>
<td>32.15 (2.25)</td>
<td>31.89 (2.62)</td>
<td>.96</td>
<td>31.4 (2.92)</td>
<td>31.83 (2.38)</td>
</tr>
<tr>
<td>TPw</td>
<td>122.97 (5.04)</td>
<td>122.86 (6.17)</td>
<td>.59</td>
<td>128.46 (5.51)</td>
<td>130.68 (5.03)</td>
</tr>
</tbody>
</table>

Data are presented as mean (SD) in mm, and P values are shown.

al = Articular line. FCw = Bicondylar width. FINw = Femoral intercondylar notch width. ICIESw = Intercondylar intereminence space width. LFCh = Lateral femoral condyle height. LFCw = Lateral femoral width. MFCh = Medial femoral condyle height. MFCw = Medial femoral condyle width. MICETh = Medial intercondylar eminence height. pf = Popliteal fossa. TPw = Tibial plateau width.

*Significant values.
Figure 2—A—Study 1 femoral condyle radiographic measurements taken at the level of the popliteal fossa (pf) on caudo-15°-proximal–craniodistal radiographs in subchondral radiolucent (SR+ and SR−) group radiographs. SR− represents the healthy stifles with no medial femoral condyle (MFC) SR lesions. SF+ are stifles with MFC SR lesions. The data is further subcategorized into 2 age groups: < 7 months old and ≥ 7 months old as MFC endochondral ossification, a measure of MFC maturity, is complete beyond this time point.7 a—Measurements in the SR− group. b—Measurements in the SR+ group. Each point represents a value per radiograph, per age of the horse. FCw = Femoral condylar width. LFCh = Lateral femoral condyles. MFCw = Medial femoral condyle width. MFCh = Height of the medial. *P < .0001.

B—Study 1 measurements of the intercondylar notch width (FINw) in SR− and SR+ stifle group on caudo-15°-proximal–craniodistal radiographs. SR− represents the healthy stifles with no MFC SR lesions. SF+ represents stifles with MFC SR lesions. The data are further subcategorized into 2 age groups: < 7 months old and ≥ 7 months old as MFC endochondral ossification, a measure of MFC maturity, is complete beyond this time point. a—Graph illustrating the change in size of the intercondylar notch width in SR− stifles at the level of the pf and at the level of the al. Each point represents a value per radiograph per age of the horse. No significant change in the intercondylar notch width occurred at the level of the pf with maturation, whereas a significant width reduction occurred at the level of the al level demonstrating a significant (P < .0001) focal morphological change with age in the stifle joint. b—Graph illustrating the change in size of the intercondylar notch width in SR+ stifles at the level of the pf and at the level of the al. SR+ group included stifle radiographs with lesions. Each point represents a value per radiograph per age of the horse. No significant change in the intercondylar notch width occurred at the level of the pf or the al level. *P < .0001. Radiographs depict where the corresponding measurements were performed in a 1-month-old horse (c) and a 6-month-old SR− horse (d). The white solid line illustrates the pf measurements, and the white dashed line indicates the al measurements. Further details on the definition of the al are provided (Supplementary Figure S6).

C—Study 1 tibial radiographic measurements on caudo-15°-proximal–craniodistal radiographs in SR+ and SR− stifle group radiographs. SR− represents the healthy stifles with no MFC SR lesions. SF+ represents stifles with MFC SR lesions. The data are further subcategorized into 2 age groups: < 7 months old and ≥ 7 months old as MFC endochondral ossification, a measure of MFC maturity, is complete beyond this time point.7 SR− group (a) and SR+ group (b). Each point represents a value per radiograph per age of the horse. ICIESw = Intercondylar intereminence space width; MICETH = Medial intercondylar eminence height. TPw = Tibial plateau width. *P < .0001.
of 5.1 mm for the females in the older age group. No other significant difference was noted between the right and left limbs.

**Study 2: intercondylar notch shape in SR− healthy foals postmortem**

A total of 53 radiographs were selected for study and subcategorized into a 1- to 2-month-old group (n = 34) and a 6.5- to 9-month-old group (n = 19). Data regarding sex was not available. A visual comparison of the femoral intercondylar notch drawings when arranged by group revealed a clear intercondylar notch shape change with maturation: at 1 to 2 months of age, the shape of the intercondylar notch had a larger distal aspect (A shape) that narrowed with age (Ω shape) in the older group (Figure 3).

**Study 3: limb directional asymmetry prospective assessment in 1-month-old foals at the farm: SR−**

A total of 102 stifle radiographs of 51 foals were taken. After a quality control step, 8 radiographs were excluded, leaving 94 radiographs (49 left and 46 right) for measurements. No MFC lesions were observed so all were considered SR−. Foal gender was not available.

Similar to study 1, the left FCw was significantly larger than the right (FCw_al, \( P = .038; \) FCw_pl, \( P = .024 \)). However, in contrast to study 1, both the MFCw and LFCh were significantly larger in the left limb of these 1-month-old foals (MFCw_al, \( P = .005; \) MFCw_pl, \( P = .0017; \) LFCh, \( P = .031 \)). The ICIESw on the other hand was significantly larger in the right limb (\( P = .013 \)). Although not significant, a similar trend was observed in the younger age group of study 1 (Supplementary Figure S7). No other significant differences were noted between the right and left limbs for the remainder of the parameters (Table 3).

**Table 3**—Prospective study 3 radiographic morphological measurements of the left and the right stifle of foals 1 month old without subchondral radiolucentences (SR−).

<table>
<thead>
<tr>
<th>1 month old</th>
<th>Right stifle</th>
<th>Left stifle</th>
<th>( P ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFCwpf</td>
<td>41.2 (2.88)</td>
<td>42.7 (3.07)</td>
<td>.0017*</td>
</tr>
<tr>
<td>MFCw_al</td>
<td>37.4 (2.85)</td>
<td>38.6 (3.01)</td>
<td>.005*</td>
</tr>
<tr>
<td>LFCwpf</td>
<td>41.6 (2.8)</td>
<td>41.7 (2.7)</td>
<td>.81</td>
</tr>
<tr>
<td>LFCw_al</td>
<td>38.8 (2.32)</td>
<td>38.4 (2.87)</td>
<td>.3</td>
</tr>
<tr>
<td>FCw_al</td>
<td>106 (4.9)</td>
<td>108 (5.49)</td>
<td>.024*</td>
</tr>
<tr>
<td>FCw_pl</td>
<td>104 (5.05)</td>
<td>105 (5.53)</td>
<td>.038*</td>
</tr>
<tr>
<td>MFC_h</td>
<td>55.2 (4.09)</td>
<td>55.5 (3.7)</td>
<td>.57</td>
</tr>
<tr>
<td>LFCh</td>
<td>57.4 (3.66)</td>
<td>58.5 (4.07)</td>
<td>.031*</td>
</tr>
<tr>
<td>FINw_pl</td>
<td>22.7 (3.71)</td>
<td>22.5 (3.17)</td>
<td>.72</td>
</tr>
<tr>
<td>FINw_al</td>
<td>27 (2.79)</td>
<td>27 (2.83)</td>
<td>.81</td>
</tr>
<tr>
<td>ICIESw</td>
<td>18.9 (2.21)</td>
<td>18.1 (1.97)</td>
<td>.013*</td>
</tr>
<tr>
<td>MICh</td>
<td>30.9 (2.14)</td>
<td>30.9 (2.31)</td>
<td>.91</td>
</tr>
<tr>
<td>TPw</td>
<td>103 (4.71)</td>
<td>103 (4.82)</td>
<td>.76</td>
</tr>
</tbody>
</table>

Data are presented as mean (SD) in mm, and \( P \) values are shown.

al = Articular line. FCw = Bicondylar width. FINw = Femoral intercondylar notch width. ICIESw = Intercondylar intereminence space width. LFCh = Lateral femoral condyle height. LFCw = Lateral femoral width. MFC_h = Medial femoral condyle height. MFCw = Medial femoral condyle width. MICh = Medial intercondylar eminence height. TPw = Tibial plateau width.

*Significant values.

**Discussion**

The radiographic findings offer novel insight into the maturation of the distal femur and tibia in healthy SR− stifles and reveal divergent patterns in stifles affected with MFC SR lesions that could potentially be linked to their underlying etiopathogenesis.

**Some, but not all, femur or tibia parameters increase with maturation in healthy foal stifles (SR−)**

In SR− foals of study 1, measurements of the stifle parameters (FCw, MFCw, LFCw, MFC_h, LFCh, and TPw) demonstrated an increase with age, mirroring the growth pattern described in humans and murine studies.\(^{14,34}\) The dimensions of distal femoral structures (FCw, MFCw, and LFCw) linearly increase among human subjects up to the age of 31.\(^{14,34}\) This finding underscores a continuous remodeling process occurring in the distal femur as it ages, resembling the observations we made in these foals.\(^{14}\)
Unlike the other femur parameters, the measurements of intercondylar notch (FINw) exhibited a reduction in size with maturation at its distal aspect. It transformed from an initial broad distal configuration (A shape) to a narrower one, culminating in the formation of an Ω shape as maturation progressed. These results align with similar observations documented in people. Moreover, it is also noteworthy that the shape of the intercondylar notch can exhibit slight asymmetry in certain human individuals. It is speculated that this may be due to an uneven expansion of the femoral condyles, wherein the MFC undergoes a greater enlargement compared to the LFC. Previous work has studied microstructural and histological MFC maturation in foals but did not specifically assess the intercondylar notch area. We posit that the proliferating growth cartilage and subsequent endochondral ossification of the articular epiphyseal cartilage complex of the femoral condyles may contribute to distal MFC axial growth and maturation at the articular level and narrowing of the intercondylar notch distally.

Although the equine TPw also significantly increased with age in healthy foals, the MICETH and the ICIESw dimensions did not change. These observations suggest that although the distal intercondylar notch undergoes a transformation with maturation, its opposing surface of the tibia presents a more stable morphology. Consequently, we speculate that the change in shape in the distal intercondylar notch region is a likely contributor to increases in biomechanical forces on the condyles at this site, but this hypothesis requires further investigation.

**Limb directional asymmetry is present in the stifles of healthy foals (SR−): specific femoral parameter measurements are greater in the left stifle**

A novel finding was that in healthy 1-month-old foals (study 3), the FCw, MFCw, and LFCh were all greater in the left hind limb, while the ICIESw was greater in the right hind limb. In humans, the larger left lower limbs are speculated to be a result of right-handed individuals utilizing them as stabilizing limbs. Limb lateralization is first identified in the initial weeks of fetal development, with the tibia, fibula, humerus, radius, and ulna exhibiting larger dimensions on the right side, but no asymmetry in the femur has been documented at this stage. As development progresses, the asymmetry becomes more distinct, continuing through postnatal maturation until adolescence. In adults, the long bones of the upper limbs are usually larger (diaphyseal width and length) on the right side, but in the lower limbs, bones are larger on the opposite left side, most noticeable in the femur.

There are a limited number of reports that are sometimes contradictory with respect to bone asymmetries in equine hindlimbs. Previous studies reported that many femoral parameters were larger in the right hind limb of adult racehorses, and longer third metatarsals, and larger tarsocrural joints were also measured in the right limbs of adult mixed breed horses. This was attributed to biomechanical adaptations to a preferential limb movement. However, in a CT morphometric study of adult distal femurs, no measurable differences were detected between the left and right sides.

While our study did not include fetal specimens, the identification of distal femoral asymmetry in some femur parameters in foals’ stifles as early as 1 month of age suggests that, akin to humans, asymmetry might already be established during the gestation period in horses as well, and possibly linked to intrater movement and the complex network of limb patterning in development. Preferential limb movement or sidedness has been observed in both foal and adult warmbloods. However, the switch to larger femoral parameter dimensions on the left side in adult horses may be influenced by biomechanical adaptation during exercise.

**Distinct maturation patterns were noted in the distal femur when comparing healthy foals to those with SR+ lesions**

The normal increase in MFCh and MFCw and decrease in distal FINw observed in the healthy SR− foals was not detected in the SR+ affected stifles. Moreover, limb directional asymmetry also differed between the 2 groups. Although both FCw and FINw were notably larger in the left stifles of SR− healthy foals, the MFC was significantly wider in female SR+ foals aged over 7 months, confirming right-sided limb directional asymmetry in this population. A similar trend was also observed in younger SR+ foals. The latter observations align with the greater prevalence of MFC SR lesions reported in the right limbs and the greater number of fillies (n = 66) presenting clinically for treatment compared to colts (41) in a recent case series.

A larger right MFC has the potential to increase biomechanical forces within the intercondylar notch region of the femorotibial joint, potentially leading to the development of SR lesions. This hypothesis gains support from the discovery of a larger ICIESw in the right stifle of the 1-month-old foal group in study 3. These variations in growth patterns and asymmetrical morphological features in the stifle may exert abnormal biomechanical stresses on the articular surfaces at the distal part of the MFC during movement, thus contributing to lesion formation. Differences in intercondylar space width have all been identified in cases of anterior cruciate ligament injuries or may contribute to the formation of MFC OCD in the human knee. It is important to note that the substantial limb directional asymmetry in the width of the MFC observed in older fillies with lesions could also potentially result from healing or remodeling processes triggered by the SR lesions. Additional research is needed to determine whether this observation is a causal factor or a consequential outcome.

We acknowledge that our study has certain limitations. Studies 1 and 2 were retrospective and not specifically designed to measure the chosen radiographic parameters. While our primary aim was not to directly to investigate the population prevalence
of SR, it is important to recognize that any disparities compared to previously reported data can be attributed to differences in study design. To enhance the accuracy of parameter measurements, we implemented a rigorous quality control step, resulting in the exclusion of radiographs in the current investigation. Additionally, the selection of study groups differed. In the more controlled and prospective study 3, we achieved enhanced radiographic standardization, leading to fewer excluded radiographs. Furthermore, we acknowledge that we evaluated a substantial number of variables, which increases the possibility of observing a significant effect by chance alone. It can also be argued that the imaging modality we employed is not state of the art but was the only practical option in a field setting.

This current study sets the stage for future research employing CT scans and statistical shape modeling, allowing for a more precise and comprehensive evaluation of the femoral and tibial shape changes we have identified in 3 dimensions. In conclusion, in lesion-free SR− Thoroughbred foal stifles, various morphological aspects of the maturing femur demonstrated an increase in size with advancing age, except for the FINw, which displayed distal narrowing. Conversely, except for the TPw that exhibited greater growth with age, the other measured tibial parameters surprisingly remained stable. In SR+ stifles, on the other hand, the distal femur exhibited an intriguing divergent maturation centered at the MFC, resulting in a wider MFC in the right stifle in older female foals. As SR lesions are more common on the right, this suggests a potential association with MFC morphology. The wider MFC combined with the natural narrowing of the femoral intercondylar notch could potentially contribute to repetitive traumatic impingement events at the axial MFC, inducing lesions. Further research studies are now needed to investigate this hypothesis further.

Acknowledgments

The authors sincerely thank all the field veterinarians in Equine Medical Associates, Lexington, KY, for acquiring the field radiographs for this study. We thank the technical staff at the Irish Equine Center for the specimens included in the postmortem arm of the current study.

Disclosures

Owner consent for radiographs was given. In respect to the postmortem radiographs, explicit owner-informed consent for participation in this study was not stated, but general permission for postmortem examination and retention of tissues was given.

No AI-assisted technologies were used in the generation of this manuscript.

Funding

Sheila Laverty’s laboratory is currently funded by the Natural Sciences and Engineering Research Council of Canada and by the Quebec Cell, Tissue and Gene Therapy Network-TheCell (a thematic network supported by the Fonds de recherche du Quebec-Sante).

References


Unauthenticated | Downloaded 06/25/24 08:11 PM UTC


