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Differences in foetal topographical anatomy between insertion sites of the iliopsoas and gluteus medius muscles into the proximal femur: a consideration of femoral torsion

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Background: *Prenatal twisting of the femoral neck seems to result in an angle of anteversion or torsion, but the underlying process has not been elucidated.*
Materials and methods: *This study analysed sagittal, frontal and horizontal sections of 34 embryo and foetal specimens of gestational age (GA) 6–16 weeks (crown-rump length 21–130 mm). At GA 6–7 weeks, the iliopsoas (IP) and gluteus medius (GME) muscles were inserted into the anterior and posterior aspects of the femur, respectively, allowing both insertions to be viewed in a single sagittal section.*
Results: *At GA 8 weeks, the greater trochanter and the femoral neck angle became evident, and the GME tendon was inserted into the upper tip of the trochanter. At GA 9 weeks, the location of IP insertion was to the medial side of the GME insertion. After 9 weeks, the IP insertion consisted of a wavy, tendinous part of the psoas muscle and another part of the iliacus muscle, with many fibres of the latter muscle attached to the joint capsule. After GA 12 weeks, the IP was inserted into the anteromedial side of the greater trochanter, while the aponeurotic insertion of the GME wrapped around the trochanter. At GA 15–16 weeks, a deep flexion at the hip joint caused an alteration in the relative heights of the lesser and greater trochanter, with the former migrating from the inferior to the slightly superior side.*
Conclusions: *These findings indicate that twisting of the femoral neck started at GA 8–9 weeks.* (Folia Morphol 2019; 78, 2: 408–418)

Key words: torsion, femur, neck angle, hip joint rotation, trochanter, iliopsoas muscle, gluteus medius muscle, human foetus

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INTRODUCTION

Torsion or twisting of the femur is defined morphologically as a medial (internal) tilting of the left-right axis of the femoral condyles at an angle of 10–15 degrees (angle of anteversion) relative to the long axis of the femoral neck, with some variations among human populations [12]. Thus, the effect of femoral torsion is identical to that resulting from an internal rotation at the hip joint. Evaluations of the effects of torsion on the segmental configuration of the cutaneous nerve supply in the lower extremities have shown that the segments or dermatomes are not arranged transversely but obliquely or even longitudinally relative to the long axis of the extremity. These findings suggested that an initial transverse arrangement of the dermatome in embryos is twisted internally [3, 9]. It remains unclear, however, whether torsion of the foetal femur results in twisting of the femoral skin, as little information is available on the initial development of torsion.

In contrast to the internal rotation, the lower extremities of human foetuses of gestational age (GA) > 15 weeks are highly flexed, abducted and laterally (externally) rotated at the hip joint because of the increased size of the abdomen sandwiched by the two growing thighs [4]. Moreover, crossing of foetal legs with flexed knees (i.e., strong external rotation) can save intrauterine space and result in easier delivery. Meticulous measurement of the lower extremities of 500 children of various ages showed that this intrauterine posture usually moulds the femur by external rotation, with this moulding effect usually resolving spontaneously during infancy [11]. Therefore, external rotation of the femur is more likely to be maintained from mid gestation to birth, with any prenatal torsion or internal rotation likely masked by the forced external rotation at the hip joint after mid-gestation.

In adults, the greater trochanter of the femur is located superior and lateral to and on the posterior side of the lesser trochanter. A band-like tendon from the gluteus medius (GME) muscle is inserted into the tip of the greater trochanter, and the iliopsoas (IP) tendon is inserted into the lesser trochanter. In human foetuses of GA 6–8 weeks, however, the IP is inserted immediately anterior to the site of GME insertion [10]. Thus, these two insertions and future greater and lesser trochanters can be viewed in a single sagittal section. The topographical relationship between the greater and lesser trochanters seems therefore to be altered after GA 9 weeks.

Previous studies of the foetal development of femoral torsion have utilised hard tissue specimens from human foetuses [7, 12]. However, hard tissue specimens are difficult to obtain from early foetuses and they never contain muscle insertions. The present study was designed to assess the topographic alterations in the sites of insertion of the IP and GME tendons into the proximal femur. Although torsion, twisting and rotation of the femur are three-dimensional events, we hypothesized that systematic evaluations of a set of sagittal, frontal and horizontal sections would provide critical information for morphologic evaluations.

MATERIALS AND METHODS

This study was performed in accordance with the provisions of the Declaration of Helsinki 1995 (as revised in 2013) and was approved by the ethics committee of the university. Serial sections of the hip and thigh from 34 embryos and foetuses of GA 6–16 weeks (crown-rump length 21–130 mm) were evaluated, including 6 specimens each of GA 6–7, 8, 9–10, and 12 weeks; and 10 specimens of GA 15–16 weeks. The topographical relationships between the greater and lesser trochanters and between the sites of insertion of the IP and GME muscles into the proximal femur were compared in sagittal sections of 10 specimens, frontal sections of 6, horizontal sections of 8 and tilted horizontal sections (i.e., intermediate planes between the horizontal and frontal sections) of 10. Although horizontal sections may be most suitable for assessing the anteroposterior and mediolateral relationships between the greater and lesser trochanters, these sections had the disadvantage that they could not show the entire shapes of the IP and GME muscles.

All sections were from the large collection kept at university, with the specimens derived from miscarriages and ectopic pregnancies at the Department of Obstetrics of the University. All specimens were fixed with 10% formalin solution for 1–2 weeks. Most sections were stained with haematoxylin and eosin (H&E), with other sections stained with azan, orange G or silver stain. A Nikon Eclipse 80 camera was used to visualise and photograph the sections.

RESULTS

Examination of 6 specimens of GA 6–7 weeks showed that the IP was inserted into the anterior aspect of the femur and the GME into the posterior aspect. Both insertions were visible on a single sagittal or nearby section (Fig. 1A–C). Moreover, the supero-inferior levels of these muscle insertions were almost equal. The greater trochanter consistently started to develop at the attachment of the GME tendon (Fig. 1A), while a cartilaginous lesser trochanter was not present. The head, neck and shaft of the femur were arranged in an almost straight line without a neck angle. Thus, the proximal femur appeared to push the acetabulum in an upward direction. However, a plate of the ilium was tilted at various angles, depending on the specimens. At the location of IP insertion, the psoas muscle provided a thick tendon associated with muscle fibres of the iliacus part of the IP.

Examination of the 6 specimens of GA 8 weeks showed that the anteroposterior relationship of the IP and GME insertions was generally maintained, but that both insertions could not be included in a single sagittal section (Fig. 1D–F). A gap of 0.2–0.4 mm in the anteroposterior axis was observed between the sites of insertion (cf., diameter of the femoral head: 0.5–0.7 mm), making the site of IP insertion slightly medial to the site of GME insertion. The tip of the greater trochanter was consistently located on the superior side of the IP insertion. A plate of the ilium was erect, with an almost straight line from the ilium to the femoral shaft (Fig. 1E). The greater trochanter appeared as a cartilaginous upward protrusion, with a developing neck angle (Fig. 1F). GME fibres converged to form a thick tendon reaching the tip of the greater trochanter. The psoas part of the IP converged to form a long tendon that wrapped around the femoral head (Fig. 1D). The iliacus part of the IP also converged into the psoas tendon, but the muscle fibres of the former ran along the tendon toward the femur. The supero-inferior levels of the IP and GME insertions were almost equal, as were the heights of the femoral head and the upper tip of the greater trochanter.

Evaluation of the 6 specimens of GA 9–10 weeks showed that the location of IP insertion had changed to the inferomedial side of the greater trochanter, and that the lesser trochanter appeared as a cartilaginous tuberosity (Fig. 2). In contrast to earlier specimens, the GME tendon became unclear and the muscle fibres appeared to be directly inserted into the superolateral aspect of the greater trochanter (Fig. 2D). The IP insertion was composed of a tendinous part from the psoas and a muscular part from the iliacus (Fig. 2B). Muscle fibres of the iliacus were attached to and inserted into a loose and thick perichondrium of the femur near the future lesser trochanter (Fig. 2A, B). The neck angle reached 120 degrees and the femoral head was 0.5–1.0 mm medial and posterior to the greater trochanter (cf., diameter of the head: 0.7–1.0 mm). However, the femoral head was still located at almost the same supero-inferior level as the greater trochanter.

Assessment of the 6 specimens of GA 12 weeks showed that the femoral head was large (diameter 1.8–2.5 mm) and pushed the tilted plate of the ilium superomedially (Figs. 3, 4). As the femoral neck increased in length, the head was 2.5–3.5 mm medial to the greater trochanter, but at the same supero-inferior level (Figs. 3F; 4C, F), possibly because of the excess neck angle of almost 90 degrees. The GME was inserted aponeurotically, wrapping around the lateral aspect of the trochanter to reach its distal end. The GME aponeurosis was fused with the insertion of the gluteus minimus muscle (Figs. 3D, 4C). Muscular insertion of the GME was still evident (Fig. 4D), and the IP tendon was wavy near the femur (Figs. 3E, 4G). Muscle fibres of the iliacus were attached to the femur (Figs. 3D, 4G) and inserted into the joint capsule (Fig. 4D). The obturator externus tendon ran across a large intertrochanteric fossa (Fig. 4B). After 12 weeks, the near frontal sections did not contain the head, neck and proximal shaft of the femur because the femoral head was directed posteriorly by torsion (Figs. 4, 5).

Examination of the 10 specimens of GA 15–16 weeks showed that, because of deep flexion at the hip joint, the location of the lesser trochanter relative to the greater trochanter had changed, from the inferior to the superior side (Figs. 5, 6). The lesser trochanter became evident as a cartilaginous projection (Figs. 5A, 6D), whereas the size of the femoral head (diameter 2.2–3.0 mm) was relatively stable. The IP tendon was wavy near the femur (Figs. 5A, C; 6D). Iliacus muscle fibres were attached to the femur (Figs. 5A, B; 6D) and inserted into the joint capsule (Fig. 5D). The GME muscle was inserted into the superficial side of the aponeurotic insertion in 4 of the 10 specimens of GA 15–16 weeks (Fig. 5F). Thus, the GME insertion consisted of (1) a muscular part attached to the trochanter with an excess muscle mass or a "slack" reaching the anterior side of the greater trochanter (Figs. 3A, 6A) and (2) an aponeurotic part

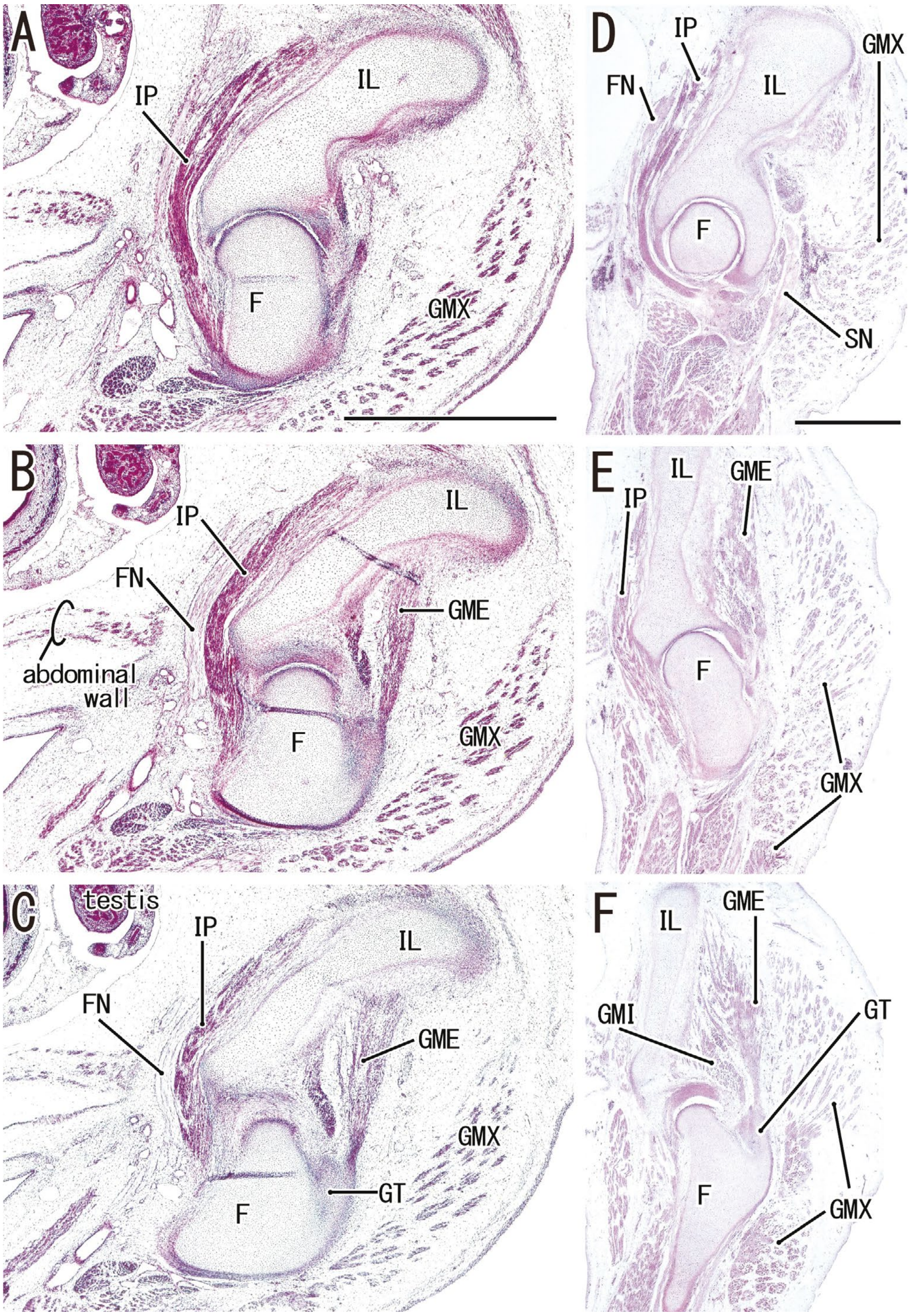

Figure 1. A–F. Insertion of an iliopsoas muscle (IP) into the anterior side of the gluteus medius muscle (GME) insertion in foetuses of gestational age (GA) 6–8 weeks. Sagittal sections of specimens of crown-rump length 20.5 mm (GA 6 weeks; panels A–C) and crown-rump length 35 mm (GA 8 weeks; panels D–F). The left-hand side of each panel corresponds to the anterior side of the pelvis. Panels A and D (C and F) show the most medial (lateral) sites in the specimens. All intervals between panels are 0.1 mm. In the smaller specimen, a single sagittal section (panel B) contains both an IP tendon and another insertion of the GME. However, in the larger specimen, the IP tendon wrapped around the femoral head (panel D) 0.2 mm medial to the site of GME insertion (panel F). The head and neck of the femur are slightly tilted with respect to the shaft (panel F). In both specimens, the GME insertion appeared to be tendinous (panels C and F) and the femur head is small and directed upward. Panels A–C (and D–E) were prepared at the same magnification (scale bars in panels A and D: 1 mm).

Common abbreviations: AM — adductor magnus muscle; F — femur; FN — femoral nerve; GME — gluteus medius muscle; GMI — gluteus minimus muscle; GMX — gluteus maximus muscle; GT — greater trochanter; IL — ilium; IP — iliopsoas muscle; LT — lesser trochanter; OE — obturator externus muscle; OI — obturator internus muscle; RF — rectus femoris muscle; TFL — tensor fasciae latae muscle; SA — sartorius muscle; SN — sciatic nerve; VI — vastus intermedius muscle; VL — vastus lateralis muscle.

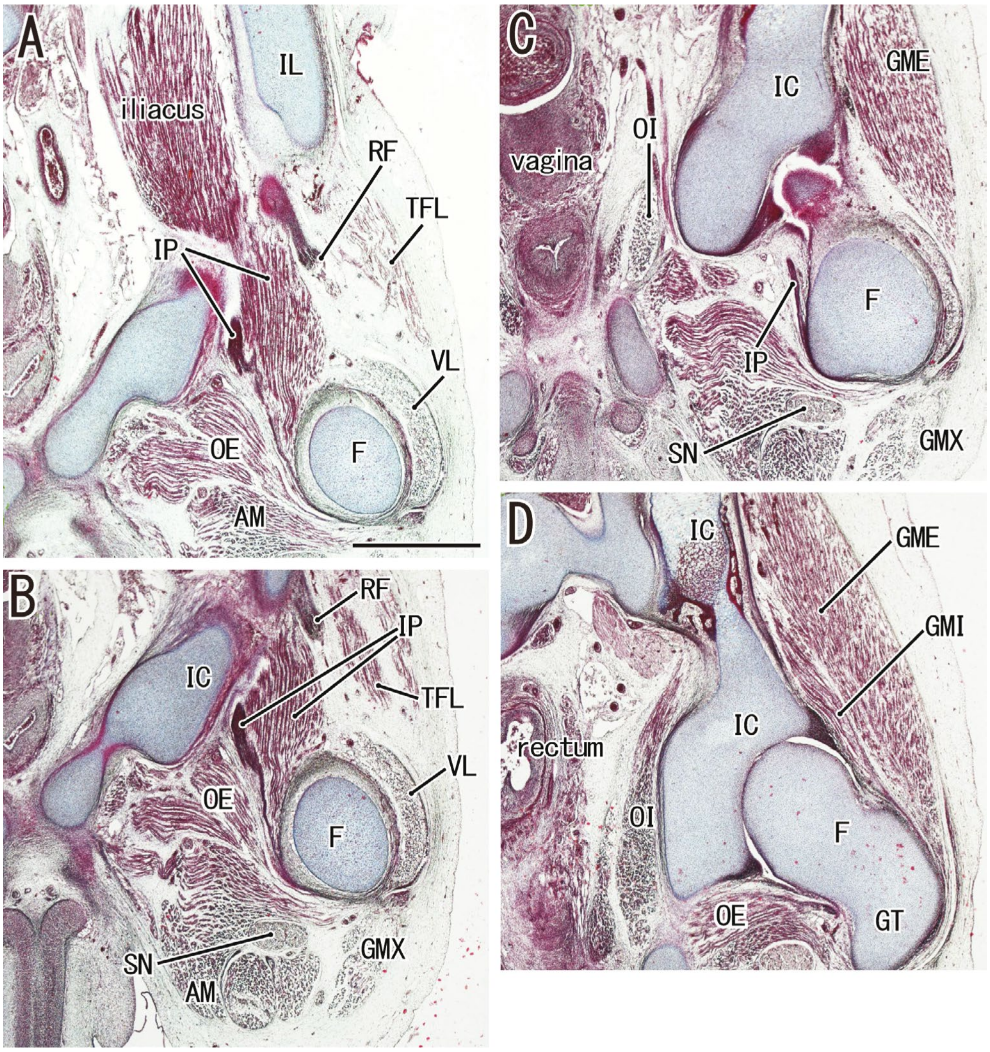

Figure 2. A–D. A slightly wavy tendon of the iliopsoas muscle (IP) on the inferomedial side of the gluteus medius muscle (GME). Tilted horizontal sections of a specimen of crown-rump length 40 mm (gestational age 9 weeks). The left-hand side of each panel corresponds to the medial side of the pelvis. Panels A and D show the most inferior and superior sites in the figure, respectively. Intervals between panels are 0.1 mm (A–B), 0.3 mm (B–C) and 0.5 mm (C–D). The insertion of the IP is composed of a tendinous part from the psoas and a muscular part from the iliacus (panels A and B). The GME does not have a definite tendon but a muscular insertion along the superior aspect of the greater trochanter (GT in panel D). The femoral head is pointed posteromedially. All panels were prepared at the same magnification (scale bar in panel A: 1 mm). Abbreviations — see Figure 1.

wrapped around the entire surface of the greater trochanter. However, a lower magnification view (Fig. 6B) provided the erroneous impression that the GME was simply inserted into a tip of the trochanter, as in samples of GA 6–7 weeks. In addition, as seen in the iliacus part of the IP, the gluteus minimus muscle belly was attached to a large area of the femur (Fig. 5C, D). Consequently, after 12 weeks, the IP insertion or lesser trochanter was shifted to the anteromedial side of the greater trochanter.

DISCUSSION

The present study showed that the drastic changes in morphology of the proximal femur in foetuses altered the topographical relationship between insertions of the IP and GME. Figure 7 summarises these observations. At the earliest stage, GA 6–7 weeks, a very short neck along a straight line from the shaft to the head of the femur provided no neck angle or torsion. The IP and GME were inserted into the femur at the same supero-inferior level (Fig. 7A). This

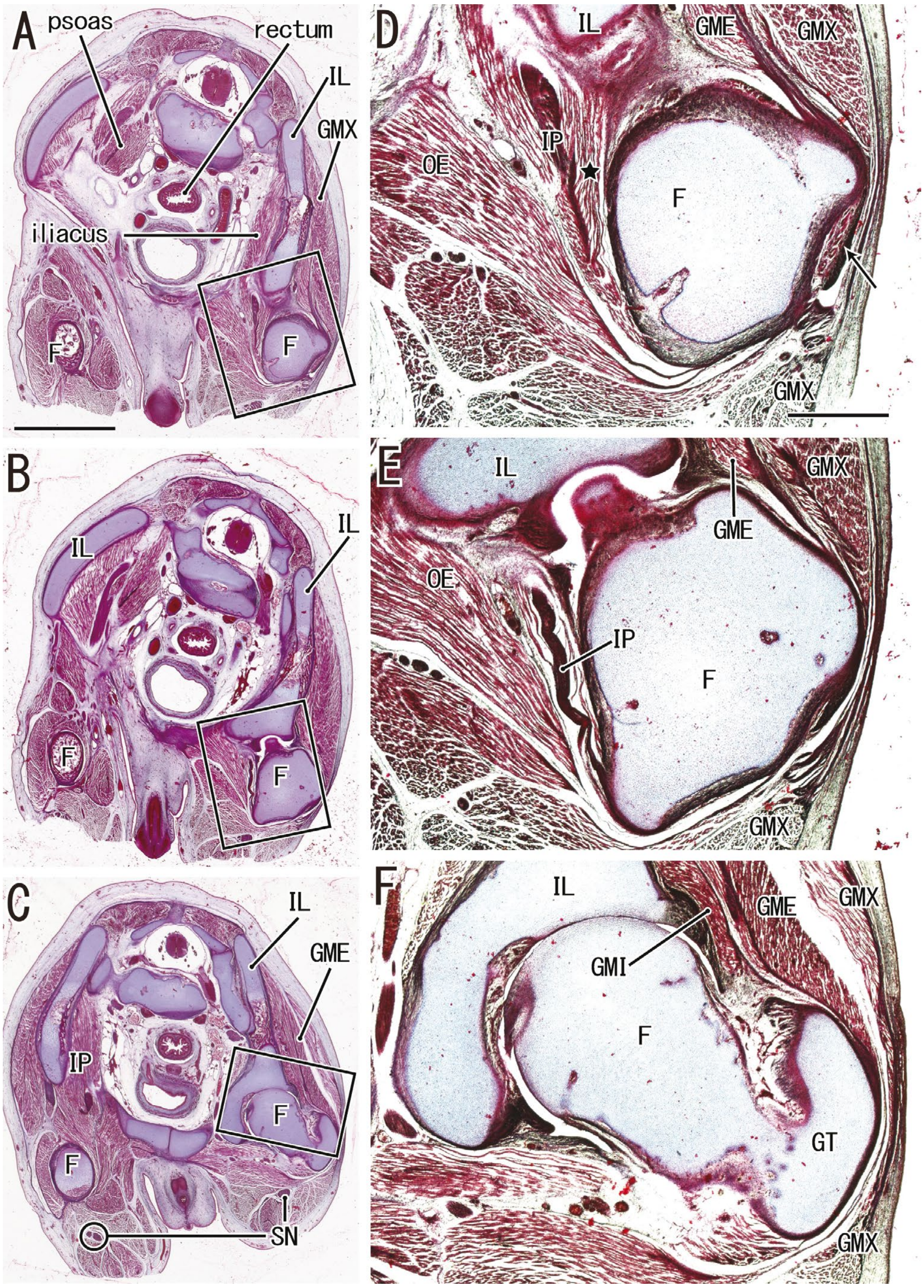

Figure 3. A–F. A slightly wavy tendon of the iliopsoas muscle on the almost medial side of the gluteus medius muscle (GME). Horizontal sections of a specimen of crown-rump length 82 mm (gestational age 12 weeks). The upper side of each panel corresponds to the posterior side of the pelvis. Panels A–C display topographical anatomy at lower magnification, while panels D–F are higher magnifications of the squares in panels A–C, respectively. Panels A and D (C and F) show the most inferior (superior) sites in the figure. Intervals between panels are 0.3 mm (D–E) and 0.6 mm (E–F). The psoas tendon exhibits a slightly wavy course (panel E), while the iliacus muscle fibres (asterisk in panel D) are attached to the femur. The GME does not have a definite tendon, but the muscle fibres are attached to the posterolateral aspect of the greater trochanter. The arrow in panel D indicates excess muscle fibres of the gluteus medius reaching the anterior side of the trochanter. The femoral head is directed posteromedially. Panels A–C (and D–F) were prepared at the same magnification. Scale bar: 3 mm in panel A; 1 mm in panel D. Abbreviations — see Figure 1.

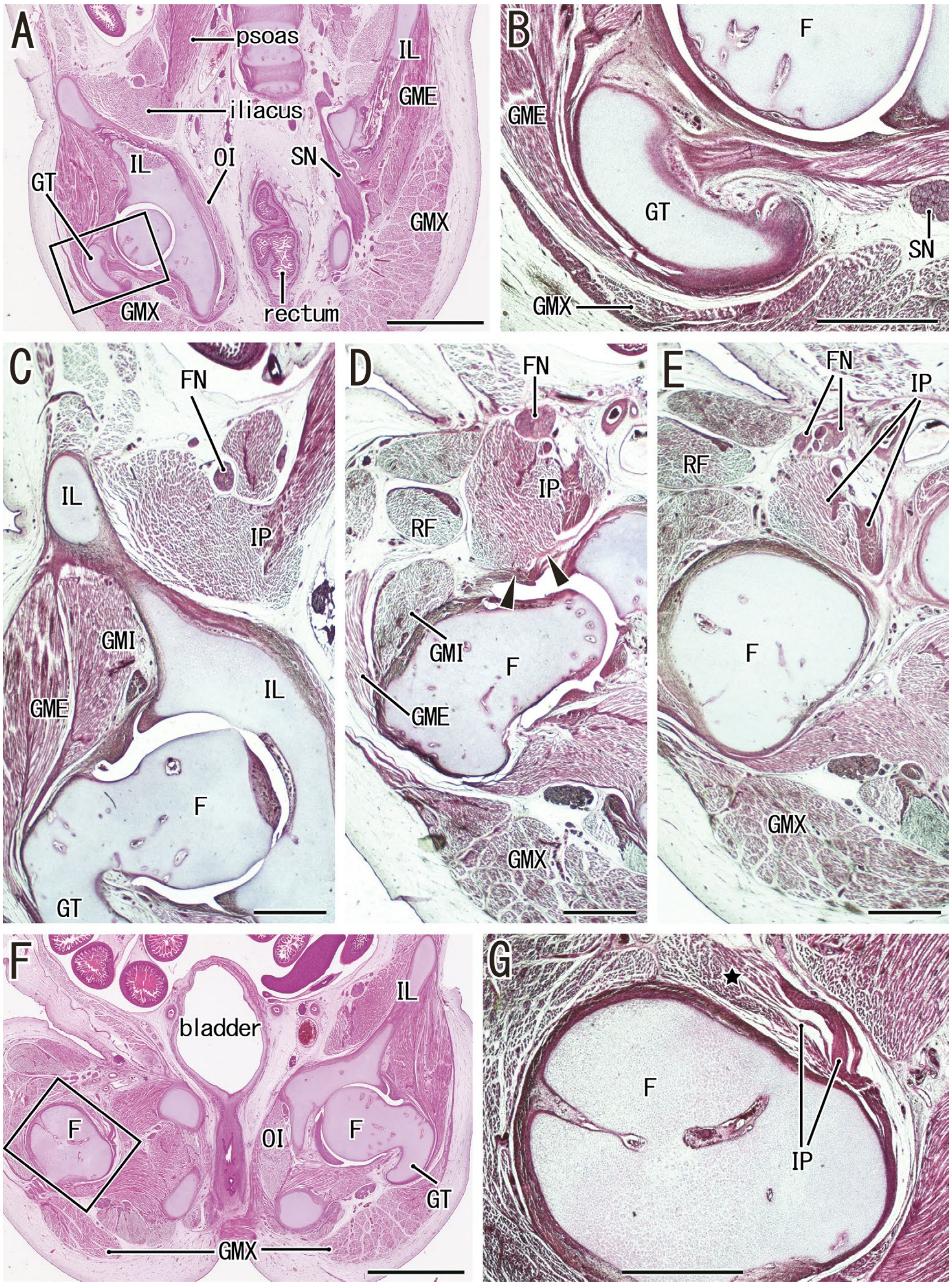

Figure 4. A–G. A slightly wavy tendon of the iliopsoas muscle on the anteromedial side of the gluteus medius muscle (GME). Frontal sections of a specimen of crown-rump length 85 mm (gestational age 12 weeks). The upper side of each panel corresponds to the superior side of the pelvis. Panels A and F display topographical anatomy at lower magnification, while panels B and G are higher magnifications of the squares in panels A and F, respectively. Panels A and B (F and G) show the most posterior (anterior) sites in the figure. Panels C–E exhibit planes between panels A and F. Intervals between panels are 0.4 mm (B–C), 0.7 mm (C–D), 0.5 mm (D–E) and 0.7 mm (E–G). Fibres of the GME converge to a tendon wrapping around the greater trochanter (GT in panel B). The iliopsoas tendon exhibits a slightly wavy course (panel G) in association with muscle fibres attaching to the joint capsule (arrowheads in panel D). The femoral head is directed medially. Scale bar: 3 mm in panels A and F; 1 mm in the other panels. Abbreviations — see Figure 1.

morphology was similar to that of infraspinatus and subscapularis muscle insertions, which wrap around the humerus head during early development [1]. These findings suggest that this configuration is common to muscles surrounding a multiaxial spheroidal joint. After GA 8 weeks, the femoral neck became elongated and the angle of inclination increased, resulting in an excess neck angle of almost 90 de-

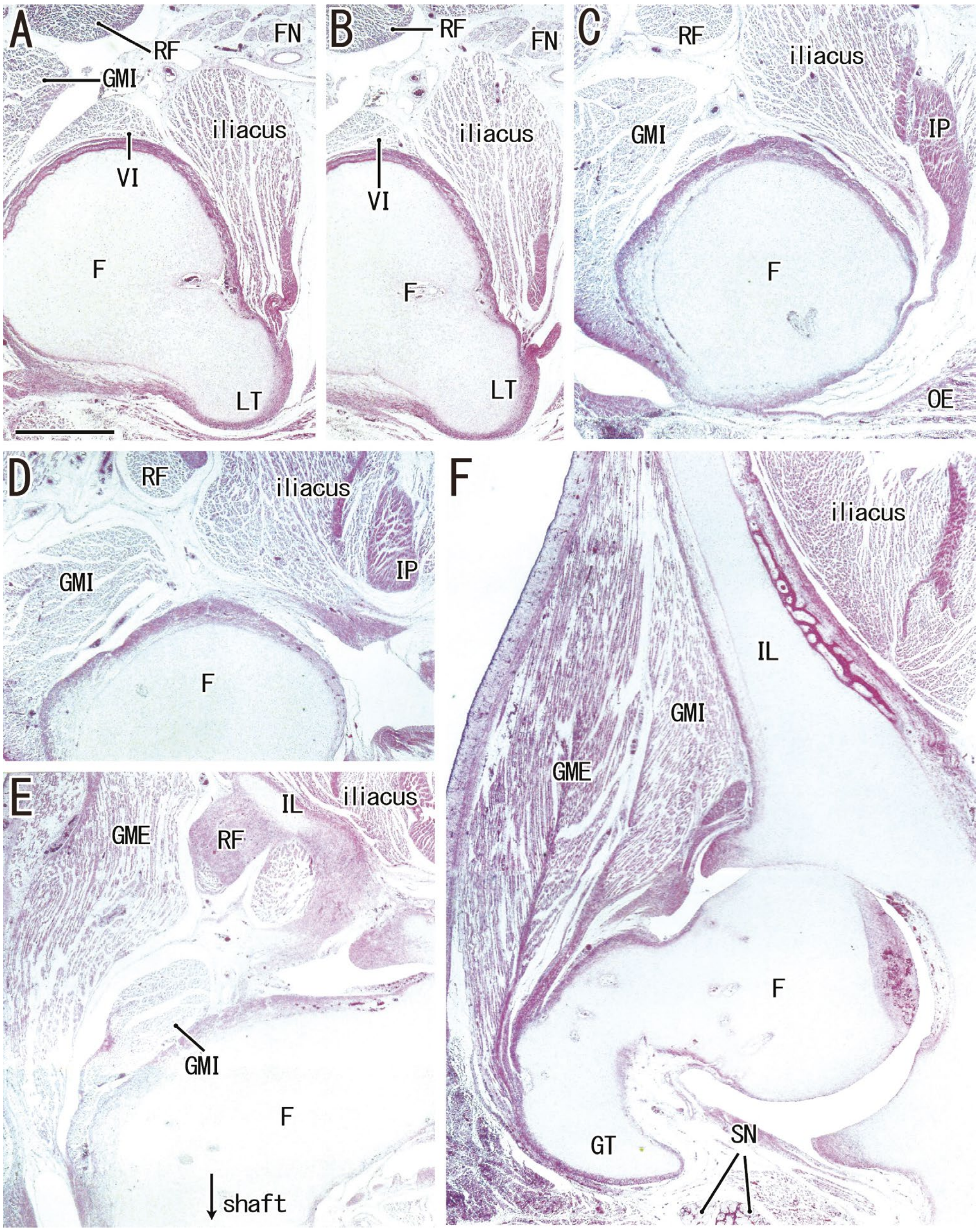

Figure 5. A–F. A lesser trochanter receiving a wavy tendon of the iliopsoas. Frontal sections of a specimen of crown-rump length 110 mm (gestational age 15 weeks). The right-hand side of each panel corresponds to the medial side of the pelvis. Panels A and F represent the most anterior and posterior sites in the figure, respectively. Intervals between panels are 0.2 mm (A–B, B–C), 0.6 mm (C–D), 0.8 mm (D–E) and 1.0 mm (E–F). Panel B contains an intramuscular tendon of the iliacus and another tendon (arrow) from the psoas; these two tendons of the iliopsoas join in panel C. These iliopsoas tendons are wavy (panels A–C), while the tendon of the gluteus medius muscle is straight (panel F). The greater trochanter is 2.6 mm posterior and 3–4 mm lateral to the lesser trochanter. The iliacus muscle fibres are attached to the femur near the lesser trochanter (panels A and B). All panels were prepared at the same magnification (scale bar in panel A: 1 mm). Abbreviations — see Figure 1.

grees (cf., 120 degrees in adults). This may facilitate movements of the hip joint, even *in utero*. Torsion of the femur seemed to occur at GA 8–9 weeks (Fig. 7B) and may subsequently increase in response to a physiological external rotation at the hip joint to maintain a crossing of foetal legs with flexed knees. Because the relative positions of the two trochanters changed, torsion should occur at the femoral shaft distal to the trochanters.

At GA 12–16 weeks, the IP tendon loosened, providing a wavy course, and the straight GME insertion (muscular and tendinous) wrapped around the curved, lateral aspect of the greater trochanter. These alterations may have been due to internal rotation

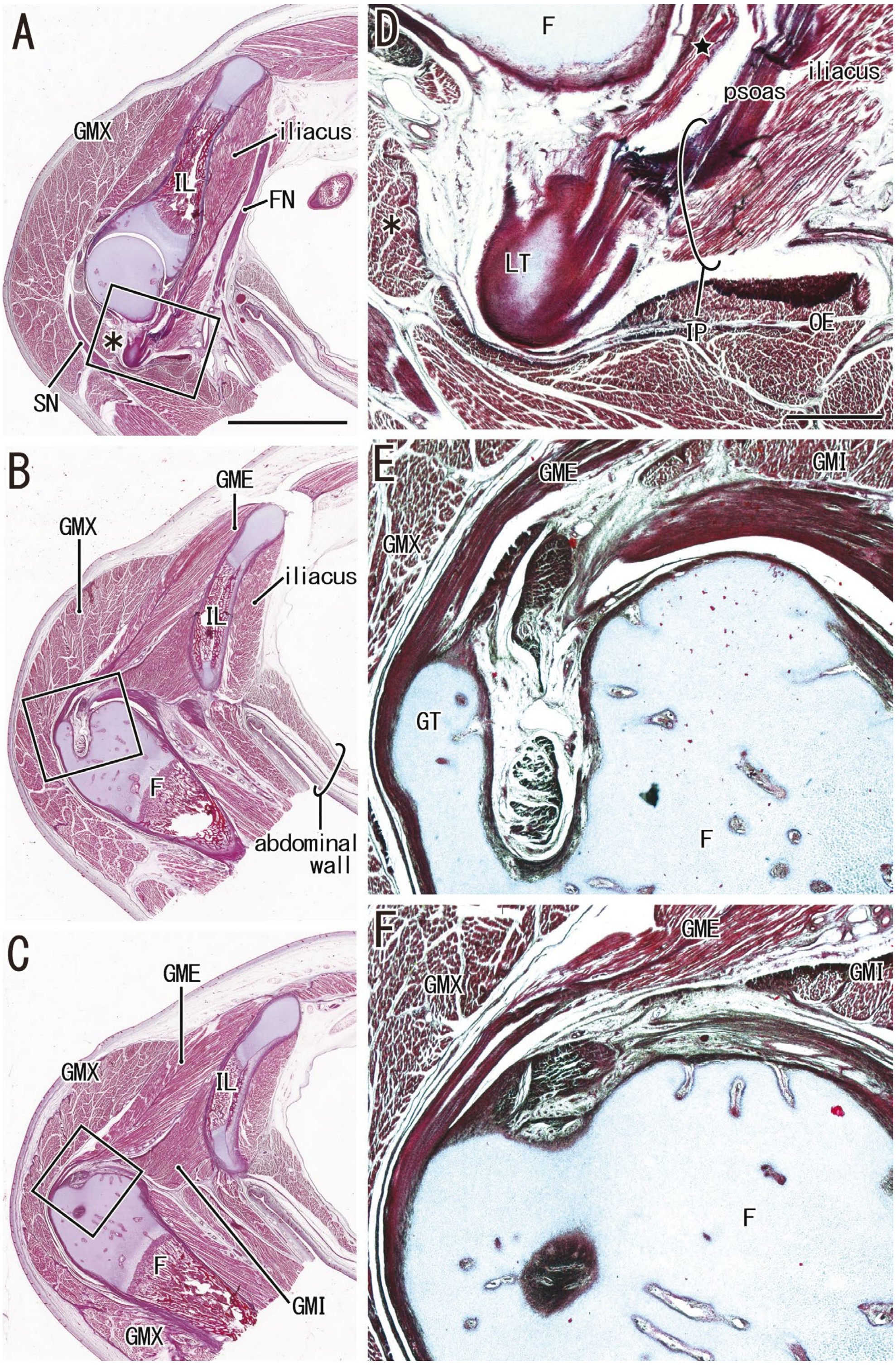

Figure 6. A–F. A cartilaginous lesser trochanter on the superior side of the gluteus medius tendon. Horizontal sections of a specimen of crown-rump length 130 mm (gestational age 16 weeks). The upper side of each panel corresponds to the posterior side of the pelvis. Panels A-C display topographical anatomy at lower magnification, while panels D–F are higher magnifications of squares in panels A–C, respectively. Panels A–C were prepared at the same magnification, as were panels D–F. Panels A and C represent the most superior and inferior sites in the figure, respectively. Intervals between panels are 1.5 mm (A–B) and 0.5 mm (B–C). A thick and wavy tendon of the psoas is inserted into the lesser trochanter (LT in panel D). Parts of iliacus muscle fibres converge to the tendon, while the other parts (asterisk in panel D) attach to the joint capsule. The gluteus medius muscle also carries a thick and straight tendon inserting into and wrapping around the lateral aspect of the greater trochanter (GT in panels E and F). The asterisks in panels A and D indicate excess fibres of the gluteus medius muscle reaching the supero-anterior side of the trochanter. The inferiormost part of the gluteus medius is located below. Scale bar: 3 mm in panel A; 1 mm in panel D. Abbreviations — see Figure 1.

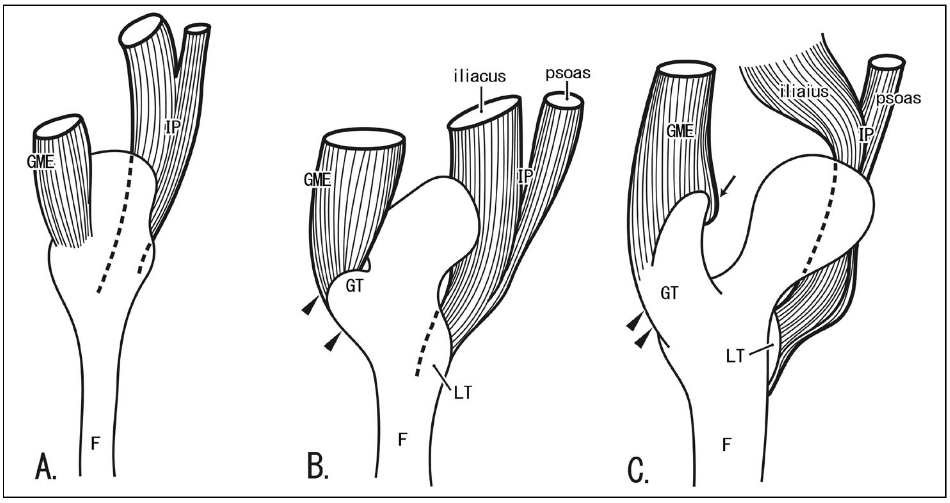

Figure 7. A–C. Summary of the study findings. Posterior views. Panel **A** shows the initial morphology of the proximal femur and its associated muscle insertions. The iliopsoas (IP) and gluteus medius (GME) muscles are inserted to the anterior and posterior aspects of the femur, respectively. Panel **B** exhibits an intermediate morphology. The greater trochanter (GT) develops first, followed by the development of the lesser trochanter (LT). The IP and GME insertions are shifted to the medial and lateral sides of the femur, respectively. The psoas tendon is wavy near the insertion, while the GME insertion is aponeurotic, wrapping around the trochanter (arrowheads). Panel **C** shows the almost final morphology, but the GME insertion provides an excess mass of muscles (arrow) at the supero-anterior side of the trochanter; F — femur.

caused by the developing torsion. Likewise, an initial tendon-like insertion of the GME changed at GA 6–9 weeks to a thick muscular insertion, along with an aponeurosis wrapping around the greater trochanter. The GME muscle fibres seemed to be rolled along the trochanter by twisting of the femur, resulting not only in the attachment of muscle fibres to the trochanter but also an excess mass or "slack" of muscles reaching a site immediately below the trochanter. These morphologies likely indicate the developing torsion of the femur. After GA 12 weeks, the IP insertion or the lesser trochanter was located on the anteromedial side of the greater trochanter, a morphology that persists into adulthood (Fig. 7C).

In adults, the angle of anteversion is 10–15 degrees, equal to the range of twisting or torsion at GA 8–9 weeks. However, the greater (or lesser) trochanter may twist 60–90 degrees from the posterior (or anterior) side to the lateral (or anteromedial) side of the femur shaft. This estimate of 60–90 degrees was approximate, because topographical relationships may have altered in the pelvis, including the sacroiliac joint, as well as in the proximal femur. However, the discrepancy between 10–15 and 60–90 degrees suggested that migration of muscle insertions along the bony surface may have led to an over-estimate of actual twisting of the femur. Although a study of 140 foetuses at GA 12–24 weeks, but decreases slightly after GA 36 weeks [12], the present study found a drastic and critical change in morphology before GA 12 weeks.

The present study also showed that muscle fibres of the iliacus ran along the psoas tendon and then attached to the femur and were inserted into the hip joint capsule. Muscle fibres attaching to a joint capsule have been observed in many joints of human adults [5]. However, in adults, IP muscle fibres are unlikely to attach to the capsule because the IP tendon reinforces the weak anterior aspect of the joint as a dynamic stabiliser, acting as a supporting structure strengthened by muscle contractions, comparable to the relationship between the rotator cuff and the glenohumeral joint [13]. The subscapularis muscle tendon, the strongest rotator cuff tendon, showed a similar morphology [8], with this tendon in late stage foetuses composed of abundant fragments of muscle fibres [2]. Moreover, flexor muscle fibres attached to the capsule in foetal elbow joints were reported to degenerate after birth [5]. Foetal iliacus muscle fibres attaching to and along the capsule seemed to degenerate from heavy mechanical stress when the tendon pushed the femoral head in the posterior direction for stabilisation.

"Proof of torsion" has been provided by a spiral fibre arrangement in the ischiofemoral ligament covering the anterior aspect of the adult hip joint [6]. We found, however, that the joint capsule, including the supporting ligaments, was too thin to identify the expected spiral configuration. Moreover, even if present in foetuses, spiral collagenous bundles were not maintained until adulthood but were reconstructed depending on mechanical demands after birth. Likewise, an oblique or longitudinal configuration of dermatomes in the lower extremities was unlikely to be connected with the development of torsion because the courses of cutaneous nerve were apparently established before GA 8–9 weeks. Finally, the clinical relevance of prenatal torsion is difficult to determine, because little or no information is available about pathologies of the proximal femur in congenital dysplasia of the hip. This abnormality is usually attributed to a poorly developed acetabulum. However, because the shape and depth of the socket are determined by the ball, a failure of foetal torsion with an abnormal muscle insertion may be associated with some types of dysplasia of the hip.

Acknowledgements

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