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Differentiation of strains in the lateral and medial bands of the iliofemoral ligament: A segmental approach

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Abstract

Iliofemoral ligament strains have been assessed in a circumscribed portion, limiting the information regarding the strains in the proximal, mid and distal portions. The purpose of this study is to describe the longitudinal and transversal strain within the proximal, mid and distal portions of the lateral and medial bands of the iliofemoral ligament. Ten fresh cadaveric specimens were assessed. The iliofemoral ligaments were divided into medial and lateral bands. Hemispherical beads (2.6 mm) were placed on the lateral and medial borders of each band. Four positions were assessed: abduction, extension, internal and external rotations combined with extension. The hemispherical beads were scanned at the end range of motion using a laser scanner. The three-dimensional position of each bead was used to estimate longitudinal and transversal strains. A three-factor ANOVA was used to compare movements, borders, and portions within each ligament for longitudinal strains. A one-way ANOVA was used to compare transversal strains between portions. This technique showed mean reliability (ICC: 2, 1) of 0.90 ± 0.06. The external rotation showed the highest strains in both ligaments ($p < 0.05$). Abduction showed a significant difference between the lateral and medial borders in both bands ($p = 0.001$). Eight movement-border combinations showed a significant difference between proximal, medial, and lateral portions ($p < 0.005$). According to our results, there is a clear effect of portions (proximal, mid and distal) within the ligament and movements. Abduction shows the lowest strains longitudinally but the largest strains transversally. Although we do not know the impact of this phenomenon, future studies should assess the strains following hip arthroscopies. The latter might improve the impact of this procedure on hip biomechanics. Lastly, the iliofemoral ligament should be assessed using a segmental approach rather than as a complete unit.

KEYWORDS
clinical movements, hip assessment, hip joint, ligament strains

1 | INTRODUCTION

The iliofemoral ligament is the strongest and most important ligament of the hip (D'Ambrosi et al., 2021; Johannsen et al., 2019). It is usually described by the lateral and medial bands (Chu et al., 2003; Hidaka et al., 2014; Wagner et al., 2012). The lateral band of the iliofemoral ligament (LBIFL) runs between the medial part of the inferior portion of the anteroinferior iliac spine and the upper portion of the intertrochanteric line (Burkhart et al., 2020; Hidaka et al., 2014; Wagner et al., 2012). The medial band of the iliofemoral ligament (MBIFL) runs from the lateral part of the inferior portion of the anteroinferior iliac spine to the lower portion of the intertrochanteric line (Burkhart et al., 2020; Hidaka et al., 2014; Wagner et al., 2012). Both bands restrict hip extension limiting the muscular action in an erect position (Fuss & Bacher, 1991; Hewitt et al., 2001; Wagner et al., 2012). More precisely, the LBIFL limits extension, adduction, and external rotation (Fuss & Bacher, 1991; Hidaka et al., 2009). The MBIFL limits hip extension, abduction, and external rotation (Fuss & Bacher, 1991; Hidaka et al., 2009; Martin et al., 2008, 2014).

Ligament strain, i.e., the changes in length regarding an initial position, brings additional value to the clinicians (Hewitt et al., 2001; Hidaka et al., 2009, 2014; Ravary et al., 2004). Various techniques are used to measure strains such as uni-axial loading cells (Hewitt et al., 2001; Pieroh et al., 2016) and differential variable reluctant transducers (DVRT) (Estebanez-de-Miguel et al., 2020; Fleming et al., 2001; Fleming & Beynnon, 2004; Hidaka et al., 2009; 2014). However, the former does not permit to assess the ligament in situ (Hewitt et al., 2001) and the latter is unable to measure three-dimensional strains (Hidaka et al., 2014). In addition, because DVRTs are usually positioned in the middle portion of the ligament and as the ligaments do not have the same strains in their middle, proximal, and distal portions (Fleming & Beynnon, 2004; Hewitt et al., 2001), the use of DVRTs may generalize the strain measured. Recently, strains in the iliofemoral ligaments were estimated using CT-scan images and embedded zirconium-dioxide beads inserted in the ligaments (Burkhart et al., 2020). These authors stated that their study allowed to assess the strains within the ligament using a minimally invasive technique. However, they did not compare regional properties within each ligament in movements that are commonly used in clinical settings (Martin et al., 2010).

The main objective of this study is to characterize the longitudinal and transverse strains in the LBIFL and MBIFL during hip abduction, extension, and internal and external rotations combined with extension. The general hypothesis is that hip extension combined with external rotation will show the largest strains in both bands. The first specific objective is to assess strains in the lateral and medial borders of each ligament. The second hypothesis is that the borders of each band will show significantly different strains. The second specific objective is to report strains in a proximo-distal assessment within each border. The third hypothesis is that the mid-portion of each band will show the largest strains independently of the movement assessed.

2 | METHODS

2.1 | Population

Left and right lower limbs from five fresh-frozen cadaveric specimens (aged 76.3 ± 12.4 years) were used ($n = 10$). The procedures used in this study adhere to the tenets of the Declaration of Helsinki. Exclusion criteria were as follow: no surgical procedure at either the hip or the knee, no sign of limited motion, and no sign of extensive degeneration at the hip (>2 Grade of Tonnis (Tonnis & Heinecke, 1999)). Degeneration status was assessed based on X-ray imaging. The parameters were: focal distance of 100 cm and 80 kV (Bontrager & Lampignano, 2013) using a Mobile Capacitor X-ray Generator (model: SMR-16, SEDECAL, Rio de Janeiro). The pelvis was taken off the cadaver at the S1-S2 junction. Thereafter, the pelvis was separated between the left and right sides at the pubis junction anteriorly. Posteriorly, the sacrum was separated in the mid-portion of the sacral vertebrae. This procedure allowed stabilization of the hemi-pelvis and the lower limb in a side-lying position, thus facilitating the capsular scanning. Muscle mass was dissected from the pelvis to the knee. The capsular tissue was kept intact, and the iliofemoral ligaments were accurately prepared. Specimens were hardly fixed to the testing table using external fixators. The femur was held in an anatomical position using a heavy-duty clamp. The anatomical position was defined as the position of the femur relative to the pelvis in an upright position. The length of each ligament in this position was defined as the initial length for strain calculations.

2.2 | Hemispherical markers positioning

Plastic hemispherical (Ø 2.6 mm) markers were used to delineate the lateral and medial borders of the LBIFL and MBIFL. This placement was adapted from a previous study (Burkhart et al., 2020). The markers were glued to the ligament using cyanoacrylate glue (Lepage Ultra Gel, 4 mL). A small amount of acetone was applied to the insertion site using a cotton swab to improve the adhesion of the glue and avoid any falling markers. No marker fell during the entire experiment. Special attention was paid to the ligament's moisture to limit the its drying process, which could modify its structural and mechanical properties. The ligaments were kept moist by spraying saline water.

Eight and ten markers were placed on the LBIFL and MBIFL, respectively (Figure 1). The lateral and medial borders of the LBIFL had four markers each. The lateral and medial borders of the MBIFL had five markers each. The length difference between the two ligaments explains the variation in the number of markers, the MBIFL being longer than its counterpart (Wagner et al., 2012). On the lateral and medial borders of the LBIFL, the hemispherical markers were placed at a distance representing 33% ± 1% of the total length of the ligament. On the MBIFL, the markers were placed at 25% ± 1% of the length of the ligament. These steps were defined to limit between-specimen (ligament length variation) variability in the distance

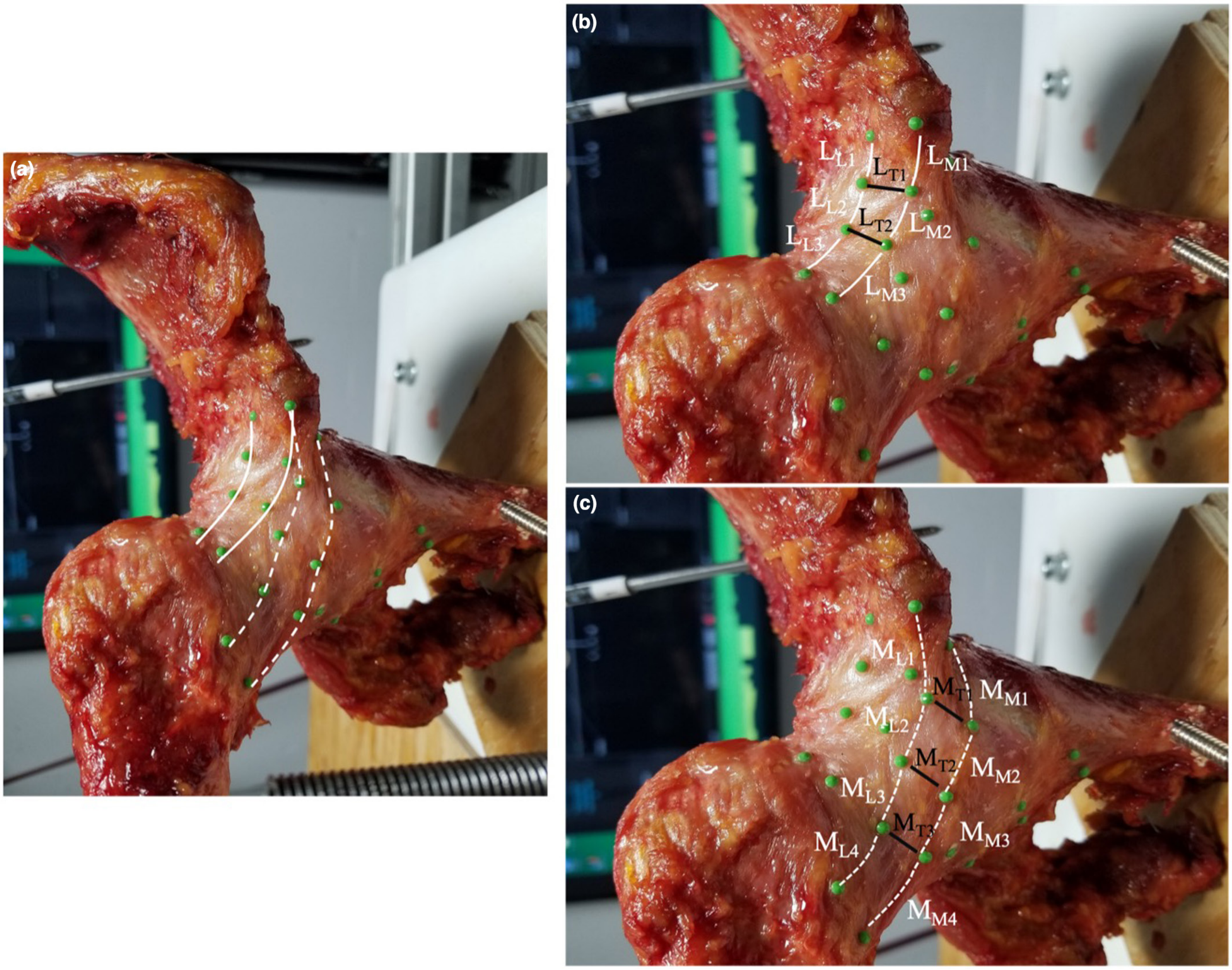

FIGURE 1 Position of the hemispherical markers on the LBIFL and MBIFL. (a) anterior view with the LBIFL (full lines) and the MBIFL (dotted lines). (b) Portions of the lateral (L_{L1}-L_{L2}-L_{L3}) and medial (L_{M1}-L_{M2}-L_{M3}) borders of the LBIFL. Two transverse portions are described within the LBIFL (L_{T1} and L_{T2}). (c) Portions of the lateral (M_{L1}-M_{L2}-M_{L3}-M_{L4}) and medial (M_{M1}-M_{M2}-M_{M3}-M_{M4}) borders of the MBIFL. Three transverse portions are described within the MBIFL (M_{T1}, M_{T2} and M_{T3}).

between markers. The lateral and medial borders spaces between markers of the LBIFL are identified as L_{L1}, L_{L2}, and $L_{L3,}$ and L_{M1}, L_{M2}, and L_{M3} from proximal to distal (Figure 1). Transversally, they were identified as L_{T1} and L_{T2}.The lateral and medial borders spaces between markers of the MBIFL are identified as M_{L1}, M_{L2}, M_{L3}, and M_{L4} and M_{M1}, M_{M2}, M_{M3}, and M_{M4} from proximal to distal. Transversally, they were identified as M_{T1}, M_{T2} and M_{T3}. This nomenclature is used in the results section.

2.3 | Hip scanning

The hip capsule was digitized with a scanner (Laser HP-L-8.9 T2, Hexagon) mounted on a Hexagon Arm (Absolute Arm, 8320, 6 Axis, Hexagon) (Figure 2). The uncertainty of measurement of the scanner is ±0.001 mm. The capsule scan was performed using several angles to digitize the tridimensional positions of all the hemispherical markers. Lower limb positions were controlled using markers placed on the femur and the pelvis to monitor the 3D movement of the femur. Using visual feedback from the optoelectronic system, the assessor placed the lower limb in the exact position between each movement. Therefore, the reliability of the ROM was not measured because it would have proved to be perfect. However, the straints' reliability was measured and reported in the results section. The first position scanned was the anatomical position, where the heavy-duty clamp helped to stabilize the femur and limit unwanted movement during the scanning. Thereafter, the following maximum amplitude positions were scanned: abduction (ABD), extension (EXT), extension combined with internal rotation (IREXT), and extension combined with external rotation (EREXT). The maximum range of motion was considered attained when a firm end feel was detected. When the maximal position was reached, the heavy-duty clamp was placed in the mid-portion of the femur. A stabilization block was placed under the heavy-duty clamp during abduction to level up the clamp. This technique was preferred while it was impossible to use mechanical help during the scanning process.

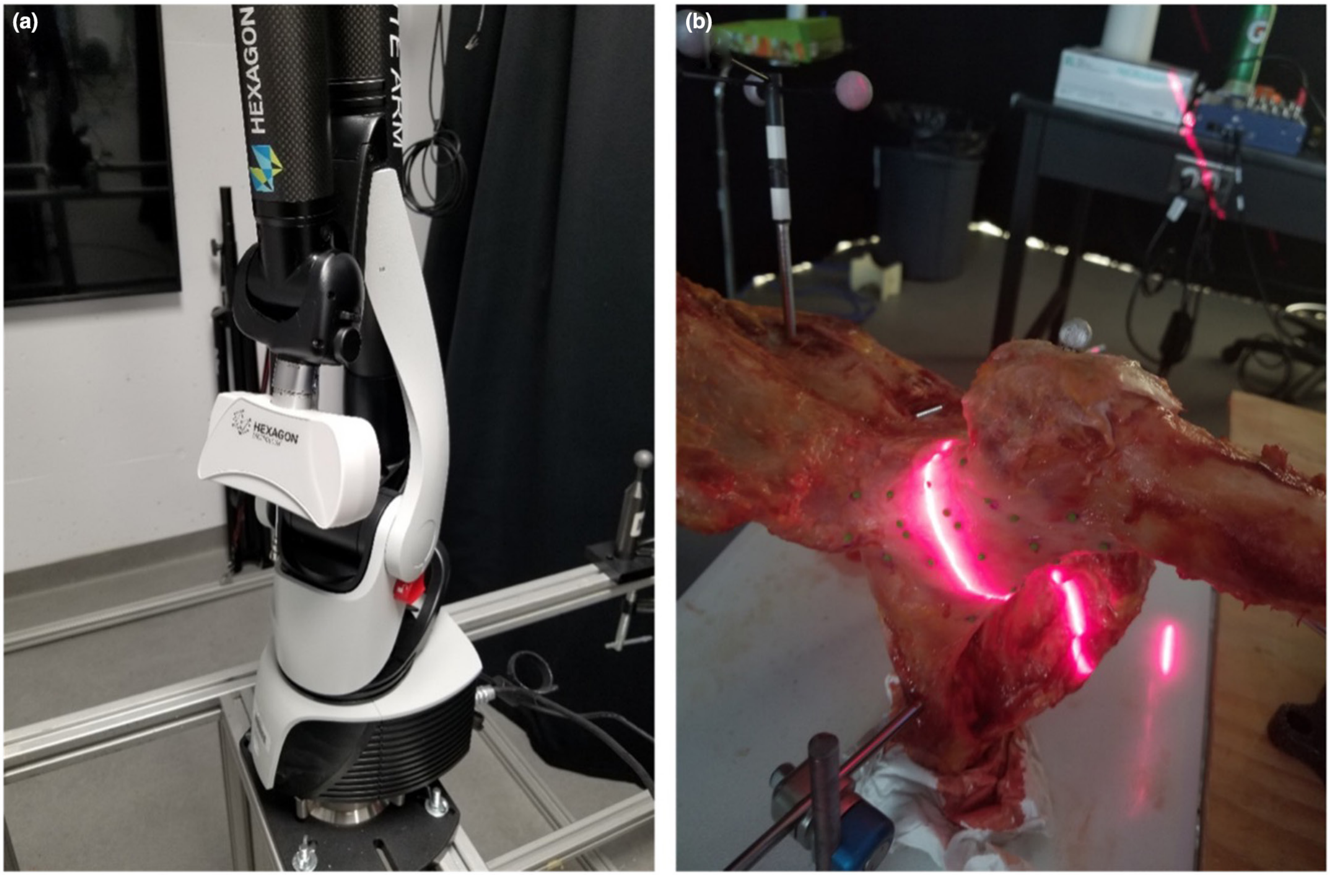

FIGURE 2 (a) Scanner mounted on the Hexagon Arm. (b) The scanning process with the scanning line.

Ranges of motion were measured using a six-camera optoelectronic system (PrimeX22, Optitrack, NaturalPoint Inc.). Ranges of motion were assessed and monitored using visual feedback from the OptiTrack application. The scanning provided a point cloud exported into STL files. These files were then exported in MeshLab to delimit each marker, and marker centers were obtained by sphere fitting in MATLAB. Thereafter, each ligament's length (*L*) and its portions were calculated and reported in mm. Strains within the ligaments were assessed using the following formula (Hidaka et al., 2014):

$$\text{Strains}\,(\%) = \frac{L - L0}{L0} \times 100$$

with *L0* its initial length in anatomical position and *L* the length of the ligament in the end-range of motion. *L0* (anatomical length) is calculated from the distance between each marker taking in consideration the anatomic curvature of the capsule. Positive (vs. negative) strains represented a lengthening (vs. shortening) of the ligament when compared to the initial length (*L0*).

2.4 | Statistical analysis

Reliability was assessed on two specimens during two separate testing sessions (1-h interval between sessions within each specimen). The same assessor performed all movements and all capsule scans. Reliability was evaluated using intra-class correlation ($ICC_{2,1}$). The ICC results were interpreted based on the following classification: under 0.50 considered poor, between 0.50 and 0.75 moderate, and between 0.75 and 0.90 good. ICCs over 0.90 were considered excellent reliability (Portney & Watkins, 2009).

Descriptive statistics for the dependent variable (strains) such as means and standard deviations were reported for each ligament (lateral and medial), movement, ligament border (medial or lateral) and portion (proximal to distal). The dependent variable reached data normality following the Shapiro–Wilk test. Therefore, ligament strains were compared using a three-way ANOVA (movements, borders, and portions). The ANOVA was followed by the Bonferroni test to sort differences within factors. Eta-squared was reported regarding significant differences following the three-way ANOVA. The transverse strains were compared using a one-way ANOVA (portions) to report differences within ligament and movement. The overall significance level was set at 0.05.

3 | RESULTS

The reliability was excellent (>0.90) for all movements and bands except for internal rotation (two bands) and for extension (lateral band) (Table 1).

The segmental strains within each band are presented in Figure 3. The longitudinal and transversal strains are presented using a color gradation ranging from −30% to 30% of strains.

TABLE 1 Intra-class correlations for intra operator reliability of strain measurement during the movements assessed (mean ± SD).

	ABD	EXT	IREXT	EREXT
Medial iliofemoral	0.91 ± 0.05	0.93 ± 0.03	0.80 ± 0.04	0.91 ± 0.03
Lateral iliofemoral	0.95 ± 0.02	0.88 ± 0.13	0.83 ± 0.13	0.96 ± 0.01

3.1 | Medial band of the ilio-femoral ligament

Movements significantly affected the strains measured in the lateral ($p < 0.001$) and medial ($p = 0.003$) borders of the medial band of the iliofemoral ligament (Table 2). The abduction showed lower strains in the lateral border than the extension ($p < 0.001$), internal rotation ($p < 0.001$) and external rotation ($p < 0.001$). Extension showed greater

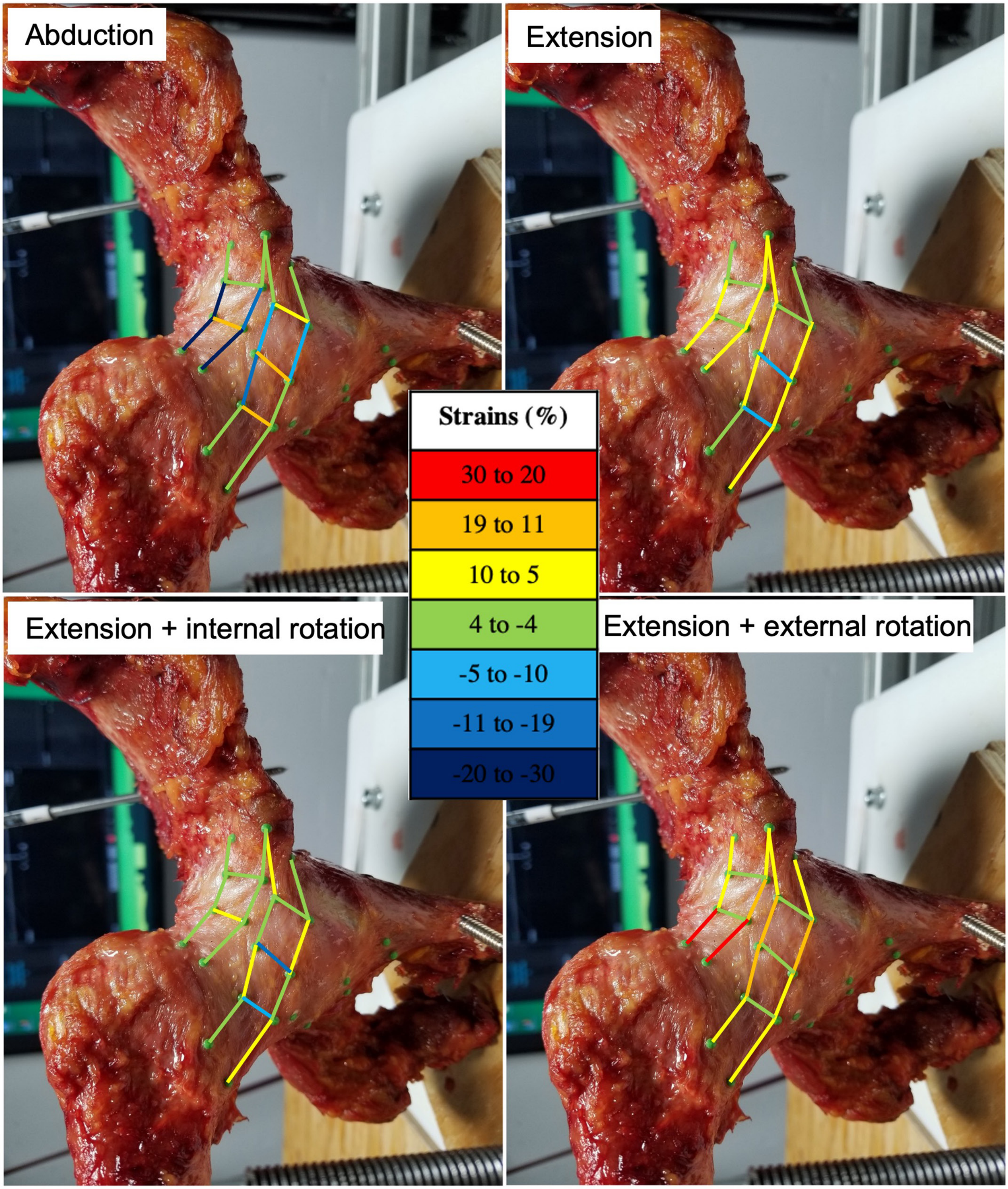

FIGURE 3 Segmental presentation of longitudinal and transversal strains within the lateral and medial band of the iliofemoral ligament.

TABLE 2 Strains (%) in the medial band of the iliofemoral ligament (MBIFL) and its different portions in the positions assessed following a three-factor ANOVA (longitudinal) (mean ± SD) and one-factor ANOVA (transversal).

	Compartment	ABD	EXT	IREXT	EREXT	*p* value
Longitudinal strains	Lateral border	−6.3 ± 7.9	7.2 ± 4.3	3.8 ± 3.9	10.4 ± 5.1	**<0.001**
	Medial border	−1.3 ± 3.7	6.7 ± 4.5	4.4 ± 5.9	8.3 ± 5.2	**0.003**
	p value	**0.001**	0.360	0.563	0.081	
	M_{L1}	−1.1 ± 1.8	8.1 ± 3.3	6.0 ± 3.3	10.1 ± 4.3	
	M_{L2}	−7.6 ± 6.3	6.8 ± 3.3	4.2 ± 4.0	10.5 ± 7.5	
	M_{L3}	−16.9 ± 4.1	9.9 ± 5.2	4.8 ± 3.6	11.4 ± 5.0	
	M_{L4}	0.34 ± 3.2	4.1 ± 3.4	0.2 ± 3.0	9.6 ± 3.7	
	p value	**<0.001**	>0.190	**<0.009**	1.000	
	M_{M1}	2.4 ± 2.1	2.7 ± 2.3	−1.6 ± 2.2	6.1 ± 4.1	
	M_{M2}	−5.1 ± 3.2	9.6 ± 5.2	7.1 ± 4.3	11.0 ± 7.1	
	M_{M3}	−3.0 ± 1.2	6.6 ± 3.8	2.6 ± 2.1	7.1 ± 3.7	
	M_{M4}	0.3 ± 2.1	7.8 ± 3.7	9.4 ± 6.5	8.8 ± 4.6	
	p value	**<0.013**	**<0.036**	**<0.010**	>0.414	
Transversal strains	M_{T1}	7.7 ± 3.7	−3.0 ± 5.2	0.1 ± 5.5	2.3 ± 3.6	
	M_{T2}	18.4 ± 8.9	−8.6 ± 3.3	−12.3 ± 7.6	1.1 ± 8.3	
	M_{T3}	15.4 ± 8.5	−5.4 ± 5.2	−9.8 ± 9.1	1.1 ± 8.5	
	p value	**<0.017**	0.080	**<0.047**	1.000	

Bold indicates significant difference ($p < 0.05$).

strains in the lateral border than the internal rotation ($p = 0.002$) and lower strains than the external rotation ($p = 0.029$). Internal rotation showed lower strain than external rotation ($p = 0.001$). In the medial border, abduction showed lower strains than extension ($p < 0.001$), internal rotation ($p = 0.010$), and external rotation ($p = 0.004$). No significant difference was observed among extension, internal rotation, and external rotation in the medial border.

The abduction movement was the only movement showing a significant difference in strains between the lateral and medial borders of the medial iliofemoral ligament. The lateral border showed lower strains (−6.3 ± 7.9%) than its medial counterpart (−1.3 ± 3.7%) ($p = 0.001$). No significant difference was observed between the lateral and medial borders in extension ($p = 0.360$), internal rotation ($p = 0.563$) and external rotation ($p = 0.081$).

3.1.1 | Medial band iliofemoral ligament—Within borders (portion) strains

In the lateral border of the MBIFL, during abduction, the proximal portion (M_{L1}) showed greater strain (−1.1 ± 1.8%) than the distal mid-portion (M_{L3}) (−16.9 ± 4.1%; $p < 0.001$). The proximal mid-portion (M_{L2}) showed significant lower strain (−7.6 ± 6.3%) than the distal portion (M_{L4}) (0.3 ± 3.2%; $p = 0.011$). The distal mid-portion (M_{L3}) showed significant lower strains (−16.9 ± 4.1%) than the distal portion (M_{L4}) (0.3 ± 3.2%; $p < 0.001$). In the medial border, the proximal portion (M_{M1}) (2.4 ± 2.1%) showed significantly greater strain than the two mid-portions (M_{M2}, M_{M3}) with −5.1 ± 3.2% ($p = 0.013$) and −3.0 ± 1.2% ($p = 0.002$), respectively. The distal part (M_{M4}) showed greater strain (0.3 ± 2.1%) than both mid-portions M_{M2} and M_{M3} with respectively −5.1 ± 3.2% ($p = 0.003$) and −3.0 ± 1.2% ($p = 0.021$). No significant differences were observed between both mid-portions ($p = 0.108$) and the proximal and distal portions ($p = 1.000$).

No significant difference was observed between portions in the lateral border during extension. In the medial border, the proximal portion (M_{M1}) (2.7 ± 2.3%) showed significantly lower strains than the distal portion of the border (M_{M4}) (7.8 ± 3.7%) ($p = 0.036$).

During internal rotation, within the lateral border, the only difference occurred between the distal portion (M_{L4}) and the proximal mid-portion (M_{L3}). The distal portion showed lower strains (0.2 ± 3.0%) compared to the distal mid-portion (M_{L3}) (4.8 ± 3.6%) ($p = 0.009$). Within the medial border, the proximal portion (M_{M1}) showed significantly lower strains (−1.6 ± 2.2) than the proximal mid-portion M_{M2} (7.1 ± 4.3%, $p = 0.003$), distal mid-portion M_{M3} (2.6 ± 2.1%, $p = 0.001$) and distal portion M_{M4} (9.5 ± 6.5%, $p = 0.010$).

During external rotation, no significant difference was observed between portions within each border.

3.1.2 | Medial band of the iliofemoral ligament—Transversal strains

Transversal strains in the MBIFL are reported in Table 2. During abduction, the M_{T1} showed lower strains (7.7 ± 3.7%) than the M_{T2} ($p = 0.017$). In extension, no significant difference was observed between each transversal portion. In Internal rotation combined with extension, both the mid (M_{T2}) ($p=0.01$) and distal (M_{T3}) ($p=0.047$) transverse portions showed a significantly larger decrease in strains when compared to the proximal transverse portion (M_{T1}). No significant difference was observed between the transverse portions during external rotation combined with extension ($p=0.88$).

3.2 | Lateral band of the iliofemoral

Strains measured in the lateral band of the iliofemoral ligament (LBIFL) are reported in Table 3. Globally, the abduction showed fewer strains in the LBIFL compared to extension ($p<0.001$), internal rotation ($p<0.001$), and external rotation ($p<0.001$). Extension showed greater strains than internal rotation ($p=0.018$) but lesser strains than external rotation ($p=0.022$). Internal rotation showed fewer strains than external rotation ($p=0.001$) but did not significantly differ ($p=1.000$).

The abduction movement was the only movement showing significant differences between the lateral (−18.4 ± 12.7%) and medial border (−12.6 ± 10.1%) ($p<0.001$). No difference was observed between borders among extension ($p=0.373$), internal rotation ($p=0.390$) and external rotation ($p=0.754$).

3.2.1 | Lateral band of the iliofemoral ligament—Within borders (portion) strains

During the abduction movement, in the lateral border of the LBIFL, the strains in the proximal portion (L_{L1}) were larger than in the mid and—distal portions (L_{L2} and L_{L3}) (all $p<0.001$). In the medial border, the proximal portion (L_{M1}) (−3.4 ± 4.5%) showed greater strains than the mid-portion (L_{M2}) (−14.4 ± 4.1%, $p<0.001$) and the distal portion (L_{M3}) (−20.0 ± 11.5%, $p=0.046$).

No significant difference was observed between portions within the lateral and medial borders during extension and internal rotation.

During external rotation, in the lateral border of the LBIFL, the strain was significantly lower in the proximal portion (L_{L1}) (7.0 ± 4.1%, $p=0.010$) and the mid-portion (L_{L2}) (7.5 ± 9.2%, $p=0.026$) than in the distal portion (L_{L3}) (29.4 ± 15.0%). No significant difference was observed in the medial border.

3.2.2 | Lateral band of the iliofemoral ligament—Transversal strains

The transversal strains of the LBIFL are reported in Table 3. Two out of four movements brought significant differences in strains between L_{T1} and L_{T2}. During abduction, the L_{T2} showed significantly larger strains (11.1 ± 5.2%) than its medial counterpart L_{T1} (0.8 ± 3.5%) ($p=0.001$). The internal rotation showed greater strains in the lateral transversal portions (L_{T2}) compared to the L_{T1} ($p=0.05$). No significant difference was observed transversally during extension ($p=0.603$) and external rotation combined with extension ($p=0.534$).

4 | DISCUSSION

The main finding of this study is that the strain in both bands of the iliofemoral ligament showed heterogeneity between their portions. Therefore, we confirm our first hypothesis that external rotation

TABLE 3 Strains (%) in the lateral band of the iliofemoral ligament (LBIFL) and its different portions in the positions assessed following a three-factor ANOVA (longitudinal) (mean ± SD) and one-factor ANOVA (transversal).

	Compartment	ABD	EXT	IREXT	EREXT	*p* value
Longitudinal strains	Lateral border	−18.4 ± 12.7	6.3 ± 6.0	1.9 ± 5.8	14.6 ± 14.6	**<0.001**
	Medial border	−12.6 ± 10.1	7.9 ± 5.3	0.5 ± 7.5	14.1 ± 10.9	**<0.003**
	p value	**<0.001**	0.373	0.390	0.754	
	L_{L1}	−3.1 ± 2.3	4.0 ± 3.4	4.1 ± 2.6	7.0 ± 4.1	
	L_{L2}	−22.4 ± 7.1	6.8 ± 7.7	1.9 ± 6.0	7.5 ± 9.2	
	L_{L3}	−29.8 ± 6.5	8.1 ± 6.3	−0.1 ± 7.3	29.4 ± 15.0	
	p value	**<0.001**	>0.525	>0.441	**<0.010**	
	L_{M1}	−3.4 ± 4.5	6.6 ± 4.4	−0.4 ± 3.0	8.7 ± 4.5	
	L_{M2}	−14.4 ± 4.1	8.5 ± 5.8	3.2 ± 5.5	13.0 ± 7.5	
	L_{M3}	−20.0 ± 11.5	8.5 ± 6.1	−1.2 ± 11.6	20.7 ± 15.0	
	p value	**<0.001**	>0.756	>0.461	>0.193	
Transversal strains	L_{T1}	0.8 ± 3.5	3.0 ± 4.9	1.1 ± 2.8	−0.9 ± 3.8	
	L_{T2}	11.1 ± 5.2	1.8 ± 4.0	6.0 ± 5.7	−2.3 ± 5.0	
	p value	**<0.001**	0.603	**0.045**	0.534	

Bold indicates significant difference ($p<0.05$).

combined with extension will show the largest strains in both bands of the iliofemoral ligament. The second hypothesis is only confirmed for the abduction motion showing significantly different strains between the borders of each band. Lastly, our third hypothesis is rejected since the midportion does not always show the largest strains. This is the first study to our knowledge to report transversal strain within the iliofemoral ligament during clinical movements.

4.1 | Abduction

Both ligaments shorten longitudinally during hip abduction and show an interesting strain pattern. From the medial border of the MBIFL to the lateral border of the LBIFL, strains decrease progressively from −1.3% to −18.4% (see Table 3). There was a significant difference between the medial and lateral borders of each band ($p<0.05$). The proximal portion of the medial border of the MBIFL show a lengthening of $2.4\pm2.1\%$ while the other portions of the ligament shorten. The femoral head might create a traction effect between the proximal insertion and mid portion of the ligament increasing the strains in the M_{M1}. Although each of the bands and their borders globally decrease in length longitudinally, the transversal strain behavior is different. In the MBIFL, the largest strain in transversal direction was observed in the M_{T2} ($18.4\pm8.9\%$). This strain could be explained by a bulging due to the convergence of its proximal and distal. In the LBIFL, the transversal strains were significantly higher laterally than medially (L_{T1}: $0.8\pm3{,}5\%$ vs L_{T2}: $11.1\%\pm5.2\%$, $p<0.001$). This might be explained by the largest shortening in the lateral portion compared to the medial portions of the LBIFL.

According to our results, the further away from the center of rotation the strains are measured, the greater will be the shortening of the ligament. The location of the joint center changes following hip arthroplasty (Bjarnason & Reikeras, 2015) and might affect abduction muscle strength (Asayama et al., 2005), cause hip impingement (Malik et al., 2007) and increase joint reaction forces (Rudiger et al., 2017). Hypothetically, changing the center of rotation might modify ligament strain patterns and restrictive function. As the iliofemoral ligament impacts locomotion (Duquesne et al., 2022), it might be important to accurately assess strains following hip arthroscopy.

4.2 | Extension

Previous authors have reported strains of $2.1\pm2.1\%$ and $1.89\pm1.22\%$ using a strain gauge placed in the mid-portion of the MBIFL (Hidaka et al., 2009; 2014). For the same band, we report strains of $7.2\pm4.3\%$ and $6.7\pm4.5\%$ in the lateral and medial borders of the MBIFL, respectively. The same studies reported strains of 0.30% and 2.0% in the LBIFL and these strains were lower than the ones observed in our study ($6.3\pm6.0\%$ and $7.9\pm5.3\%$). First, we used the anatomical position to set the initial length of the ligament. These studies used the ligament's toe-region (Hidaka et al., 2009, 2014). Since the strains are a percentage of change from the initial length, any change of this value may influence the measured strains. Second, the range of motion obtained in their study ($11.3\pm5.2°$) was lower than our range of motion in the same movement ($17\pm4.5°$) and this might partly explain the higher strains obtained in our study. Although that magnitudes of strains are different, the direction of strains (increase) is the same.

The segmental approach allows the description of interesting patterns in both bands. In the MBIFL the proximal portion of the of the medial border (M_{M1}: $2.7\pm2.3\%$) showed the lowest longitudinal strain. This strain is considerably different than its lateral counterpart (M_{L1} $8.1\pm3.3\%$). In the LBIFL, the longitudinal strains were evenly distributed in both of its borders. The M_{M1} showed the lowest longitudinal strains during hip extension. Hypothetically, the M_{M1} portion should be preferred in capsulotomies limiting the possibilities of iatrogenic instability following this surgical procedure (Kuhns et al., 2016). Transversally, the MBIFL and the LBIFL have different patterns. For the MBIFL, every transversal portions show a shortening and this, even though the longitudinal portions show an increase (Table 2). For the LBIFL, the transversal portions show an increase in strain. This result is counterintuitive. In fact, the longitudinal lengthening of the LBIFL should cause a decrease in its width as observed for the medial band. Therefore, it is impossible to clearly explain this phenomenon. The widening of the LBIFL could be caused by the movement of the underlying bony structures.

4.3 | Internal rotation

It has been shown that the LBIFL has restrictive capacities in internal rotation combined with extension, contrary to the MBIFL (Martin et al., 2008). Although we observed an increase in strains in both borders of the LBIFL during IREXT ($1.9\%\pm5.8\%$ and $0.5\%\pm7.5\%$), these strains were two times lower than the one measured in the MBIFL ($3.8\pm3.9\%$ and $4.4\pm5.9\%$). Globally, the addition of internal rotation in extension significantly decreased the strains in both the MBIFL and LBIFL compared to the extension alone ($p<0.02$).

The comparison between the portions showed different patterns. In the MBIFL, both borders show significant differences in strain between their portions. In the medial border, the lowest strain was observed distally ($0.2\pm3.0\%$) while it was observed proximally in the lateral border ($-1.6\pm2.2\%$). The internal rotation seems to twist the MBIFL creating this phenomenon in the extremities of each border. In the LBIFL, the addition of internal rotation seems to affect every portion except the L_{L1} (EXT: $4.0\pm3.4\%$ vs. IREXT: $4.1\pm2.6\%$). This result might be explained by the position of the portion (L_{L1}) regarding the axis of rotation and the motion of the femur. Transversal strains in the MBIFL show greater relaxation in the M_{T2} and M_{T3} portions than their proximal counterpart (M_{T1}). This result might be explained by the larger longitudinal strains observed in the distal portion of the MBIFL. For the LBIFL, the L_{T2} shows greater strains ($6.0\pm5.7\%$) than its medial counterpart (L_{T1}: $1.1\pm2.8\%$). The L_{T2} is more obliquely deviated than its medial counterpart due to the longitudinal strains, thus creating larger strains.

4.4 | External rotation

The external rotation combined with extension show the largest strains in both bands with strains reaching up to 29.4 ± 15.0%. The addition of external rotation in extension increased the strain up to 24%, 44%, 78%, and 131% in the medial and lateral borders of both the MBIFL and LBIFL, respectively. These increases are contrary to previously reported results showing a decrease in strains by adding 30 degrees of external rotation in extension (Hidaka et al., 2014). The results from this study are unexpected since the external rotation increases strains in different level of hip flexion (Burkhart et al., 2020).

In the MBIFL, the distribution of the strains within the different portions was equally distributed on both borders. In the LBIFL, both distal portion L_{L3} (29.4 ± 15.0%) and L_{M3} (20.7 ± 15.0%) showed the largest strains. Our results showed that the proximal approach of capsulotomies (Ekhtiari et al., 2017) should be kept limiting the impact on the restrictive capacities of the LBIFL. Transversally, both ligaments show minimum changes. These results describe an equal distribution of strains in both borders of both bands during EREXT. In fact, the markers might move more longitudinally than in other movements while keeping the transverse aspect of the ligament in the same dimension as the anatomical position limiting the strains.

4.5 | Limitations

This study is not without limitations. First, using cadaveric specimens might change the ligament structure and might differ from the in-vivo ligament. In addition, the lower limbs were used bilaterally on each specimen. Despite this bilateral use, the intra-specimen anatomical variability of the femur (Yin et al., 2018) and acetabulum (Vandenbussche et al., 2008) limits the effect of similarity between the two limbs. Second, we did not use a constant torque on the tested hip joint moment. Using a predetermined torque may increase variability between specimens as they have different tissue characteristics. However, we monitored the range of motion with a three-dimensional optoelectronic system and strains are within the physiological limits (Pieroh et al., 2016; Schleifenbaum et al., 2016). The ICCs provided in this study were good to excellent, showing the reliability of this technique. Lastly, we did not provide strains by using continuous kinematics. Therefore, it is impossible to determine at which moment the ligament loosens. Protocol modification would be needed to answer this question.

5 | CONCLUSION

We confirm that different portions of the iliofemoral ligaments showed heterogeneity. In fact, eight movement-border combinations showed significant difference between each portion. The largest strains were observed in the distal portion of both bands during external rotation combined with extension. This result supports the proximal approach during arthroscopy limiting the impact on the restrictive capacities of the iliofemoral ligament (Ekhtiari et al., 2017). Abduction brings significant difference in strains between both borders of the MBIFL and the LBIFL. The assessment of transversal strains might improve the understanding of ligament biomechanics and improve the assessment of the iliofemoral ligament. Lastly, the strains observed in the iliofemoral ligament show that it should not be assessed as a whole, and this might impact the development of mathematical models.

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CONFLICT OF INTEREST STATEMENT

The authors have no relevant financial or non-financial interest to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS APPROVAL STATEMENT

This study was approved by the Ethics Sub-committee of the Department of Anatomy at the University of Quebec at Trois-Rivières (CER-09-148-06.05).

PATIENT CONSENT STATEMENT

Not applicable.

PERMISSION TO REPRODUCE MATERIAL FROM OTHER SOURCES

Not applicable.

CLINICAL TRIAL REGISTRATION

Not applicable.

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