Tensile properties of the hip joint ligaments are largely variable and age-dependent – An in-vitro analysis in an age range of 14–93 years

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ABSTRACT

Introduction: Hip joint stability is maintained by the surrounding ligaments, muscles, and the atmospheric pressure exerted via these structures. It is unclear whether the ligaments are capable of preventing dislocation solely due to their tensile properties, and to what extent they undergo age-related changes. This study aimed to obtain stress–strain data of the hip ligaments over a large age range.

Methods: Stress–strain data of the iliofemoral (IL), ischiofemoral (IS) and pubofemoral ligament (PF) were obtained from cadavers ranging between 14 and 93 years using a highly standardized setting. Maximum strains were compared to the distances required for dislocation.

Results: Elastic modulus was 24.4 (IL), 22.4 (IS) and 24.9 N/mm² (PF) respectively. Maximum strain was 84.5%, 86.1%, 72.4% and ultimate stress 10.0, 7.7 and 6.5 N/mm² for the IL, IS and PF respectively. No one of these values varied significantly between ligaments or sides. The IS elastic modulus was higher and maximum strain lower in males. Lower elastic moduli of the PF and higher maximum strains for the IS and PF were revealed in the Z≥55 compared to the ≤55 population. Maximum strain exceeded the dislocation distance of the IS without external hip joint rotation in females, and of the IS and cranial IL under external rotation in both genders.

Discussion: Tensile and failure load properties of the hip joint ligaments are largely variable. The IS and PF change age-dependently. Though the hip ligaments contribute to hip stability, the IS and cranial IL may not prevent dislocation due to their elasticity.

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1. Introduction

The ligaments of the human hip joint are considered as mechanical stabilizers preventing dislocation passively (Walters et al., 2014). The fibrous complex consisting of both the ligaments and the joint capsule helps mediate additional stabilizing forces such as the hip-centralizing effects of atmospheric pressure. Given the helical orientation of the hip joint ligaments, namely the iliofemoral ligament (IL), the ischiofemoral ligament (IS) and the pubofemoral ligament (PF), they are assumed to limit the range of motion of the hip joint in addition to the bony constraints of the femur and acetabulum (Burroughs et al., 2005; van Arkel et al., 2015).

However, there is some ambiguity in the literature and it remains unclear whether the ligaments are truly preventing dislocation through their mechanical properties or whether the stabilizing effect is more effectively mediated via the muscles (Hewitt et al., 2001). Previous reports on hip joint capsule mechanics mostly apply to the ligaments only. Moreover, existing studies including our recent investigation on hip joint mechanics lack of standardization, sample size, are performed with tissues in a chemically fixed condition or include tissues with varying fiber orientations (Elkins et al., 2011; Hewitt et al., 2001, 2002). To date, it is unclear if the hip joint ligaments undergo age-related change.

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as most of the published experiments were carried out in an exclusively geriatric population.

Addressing these issues, the given experimental study aimed at obtaining mechanical data of fresh hip joint ligaments, revisiting the tensile properties of the IL, IS and PF. Using a highly standardized setting for tissue preparation, testing and evaluation we aimed at investigating age-related alterations of the ligaments in an age range of 14–93 years.

It was first hypothesized that the tensile properties of the IL, IS and PF ligaments vary between their sites (IA) and their side (IB) as well as gender (IC). The second hypothesis (II) was that the IL, IS and PF undergo an age-related decrease in elasticity. The third hypothesis was that the hip joint ligaments prevent hip joint dislocation passively given their elasticity.

2. Materials and methods

2.1. Sample acquisition and processing

Forty human hip joint capsules were removed bilaterally from 21 cadavers (9 ♀, 12 ♂) with a mean age of 59.7 ± 26.6 years (range 14–93 years) at the Departments of Forensic Medicine and Anatomy, University of Leipzig, Germany. The tissues were obtained within 48 h or less and in a fresh (anatomically unfixed) condition. Further information regarding the donors including the cause of death is given in Table 1. The university’s ethics committee approved this study (protocol number 051-15-09032015). Following surgical exposure of the ligament complex via a lateral approach to the hip joint the IL, IS and PF were resected from the acetabular rim proximally, and distally at the greater and lesser trochanter as well as at the intertrochanteric region as indicated in Fig. 1. All ligaments were precooled and shock frozen at −85 °C for storage and transportation. Further information regarding the donors including the cause of death is given in Table 1. The university’s ethics committee approved this study (protocol number 051-15-09032015). Following surgical exposure of the ligament complex via a lateral approach to the hip joint the IL, IS and PF were resected from the acetabular rim proximally, and distally at the greater and lesser trochanter as well as at the intertrochanteric region as indicated in Fig. 1. All ligaments were precooled and shock frozen at −85 °C for storage and transportation.

2.2. Partial plastination and osmotic adjustment of water content

Prior to mechanical testing, the tissues were slowly defrosted and their ends partially plastinated as described elsewhere (Hammer et al., 2014; Sichting et al., 2015). The samples’ water content was adjusted to 69% by mass, using the osmotic stress technique (Parsegian et al., 1995; Zernia and Huster, 2006) as described in our previous setup (Hammer et al., 2016, 2014; Schleifenbaum et al., 2016).

2.3. Mechanical testing

The central parts of the ligaments were sectioned before starting the uniaxial tensile test using a template for a defined region of failure. The tensile tests were carried out using a uniaxial testing machine (Zwick/Roell, Ulm, Germany and Instron, Norwood, MA, USA), equipped with a 2.5 kN load cell (relative value of accuracy 0.5%). Optical image correlation was carried out using a Q-400 system (VRS 4.4.1.354, Dantec Dynamics, Ulm, Germany) with Issta 4D software (VRS 4.4.1.354, Dantec Dynamics, Ulm, Germany). The samples were clamped with their major fiber orientation in the direction of load application. Preconditioning was then performed with a crosshead displacement v = 20 mm/min and a maximum strain of 5% (Pieroh, 2016). Following this, the samples’ cross-sections were cast in VPS Hydro 380 (Henry Schein Medical GmbH, Hamburg, Germany and REF 2112, Voco GmbH, Cuxhaven, Germany). A speckle pattern was sprayed onto the samples facilitating image correlation. Tensile data (displacement and force) were then obtained at a crosshead displacement speed of v = 20 mm/min. The abort criterion for the uniaxial testing was defined by a decrease of at least 30% of the respective maximum force level l.

2.4. Data evaluation, statistical analysis and numerical evaluation of maximum strain vs. dislocation distance

Sample cross sections were scanned from the casts at a resolution of 1200 dpi on a Perfection 7V750Pro (Seiko Epson Corporation, Sawa, Japan) and determined using Measure 2.1d software (Datatlff GmbH, Tübingen, Germany). Elastic modulus was computed as the secant modulus from the linear region of the tensile data generated on RStudio (RStudio, Inc., Boston, MA, USA). The tensile data was obtained to assess maximum stress and corresponding strain values. SPSS 23.0 software (IBM, IL, USA) and Excel 2013 (Microsoft Corporation, Redmond, WA, USA) were used to evaluate the data.

Table 1

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age [years]</th>
<th>Body length [cm]</th>
<th>Body weight [kg]</th>
<th>Cause of death</th>
</tr>
</thead>
<tbody>
<tr>
<td>♂</td>
<td>14</td>
<td>154</td>
<td>44</td>
<td>Traumatic brain injury</td>
</tr>
<tr>
<td>♀</td>
<td>18</td>
<td>174</td>
<td>61</td>
<td>Unclear, non-traumatic</td>
</tr>
<tr>
<td>♀</td>
<td>20</td>
<td>178</td>
<td>65</td>
<td>Cervical spinal cord injury</td>
</tr>
<tr>
<td>♀</td>
<td>25</td>
<td>185</td>
<td>87</td>
<td>Traumatic hematorthorax</td>
</tr>
<tr>
<td>♀</td>
<td>26</td>
<td>189</td>
<td>77</td>
<td>Peripheral vessel injury</td>
</tr>
<tr>
<td>♀</td>
<td>26</td>
<td>187</td>
<td>66</td>
<td>Heroin intoxication</td>
</tr>
<tr>
<td>♀</td>
<td>35</td>
<td>174</td>
<td>72</td>
<td>Unclear, non-traumatic</td>
</tr>
<tr>
<td>♀</td>
<td>41</td>
<td>177</td>
<td>56</td>
<td>Aspiration of foreign body</td>
</tr>
<tr>
<td>♀</td>
<td>51</td>
<td>175</td>
<td>65</td>
<td>Peripheral vessel injury</td>
</tr>
<tr>
<td>♀</td>
<td>53</td>
<td>183</td>
<td>91</td>
<td>Brain injury</td>
</tr>
<tr>
<td>♀</td>
<td>63</td>
<td>172</td>
<td>102</td>
<td>Traumatic hematorthorax</td>
</tr>
<tr>
<td>♀</td>
<td>65</td>
<td>n/a</td>
<td>98</td>
<td>Hepatic tumor</td>
</tr>
<tr>
<td>♀</td>
<td>71</td>
<td>177</td>
<td>81</td>
<td>Cardiac insufficiency</td>
</tr>
<tr>
<td>♀</td>
<td>74</td>
<td>173</td>
<td>80</td>
<td>Myocardial infarction</td>
</tr>
<tr>
<td>♀</td>
<td>76</td>
<td>159</td>
<td>47</td>
<td>Septic shock</td>
</tr>
<tr>
<td>♀</td>
<td>77</td>
<td>158</td>
<td>68</td>
<td>Ethyl-toxic liver disease</td>
</tr>
<tr>
<td>♀</td>
<td>81</td>
<td>n/a</td>
<td>87</td>
<td>Mesenteric infarction</td>
</tr>
<tr>
<td>♀</td>
<td>81</td>
<td>n/a</td>
<td>56</td>
<td>Acute kidney failure</td>
</tr>
<tr>
<td>♀</td>
<td>87</td>
<td>n/a</td>
<td>62</td>
<td>Hepatic tumor</td>
</tr>
<tr>
<td>♀</td>
<td>90</td>
<td>n/a</td>
<td>84</td>
<td>Cardiac insufficiency</td>
</tr>
<tr>
<td>♀</td>
<td>93</td>
<td>n/a</td>
<td>54</td>
<td>Cardiac insufficiency</td>
</tr>
<tr>
<td>♂, ♀, 12 ♂</td>
<td>59.7 ± 26.6</td>
<td>173.7 ± 8.9</td>
<td>70.0 ± 17.5</td>
<td></td>
</tr>
</tbody>
</table>

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statistically. The Kolmogorov-Smirnov test was used to determine normal distribution. An ANOVA test with post-hoc analysis was applied to compare the IL, IS and PF data. Side- and gender-related comparisons were performed with the Wilcoxon-Signed-Ranks test or the paired Student’s T-test. A Pearson’s test was applied for determining correlations. P values of 5% or less were considered as statistically significant. All values were presented in mean values ± standard deviations.

For a numerical comparison between maximum strain and the least distance required for dislocation, data on hip joint ligament length (Weidner et al., 2012) and fiber orientation (Fick, 1911; Lanz and Lang, 2004; Sobotta and Putz, 2004) were used. The assumed fiber angles between the acetabular rim and the hip joint ligaments in a 0° hip joint extension were 30°, 45° and 90° for the IL, IS and PF respectively (Smith et al., 2014). Mean femoral head diameters of 42.2 and 48.2 mm were used for females and males respectively (Milner and Boldsen, 2012). Polar diagrams were adapted from Weidner et al. (2012) for visualization of the ligament origins at the right acetabulum, strains accounting for more than ½ the diameter size were considered to be potentially causing dislocation.

### 3. Results

#### 3.1. Elastic modulus, maximum strain and ultimate stress were similar and not significantly different between the iliofemoral, ischiofemoral and pubofemoral ligaments

The mean elastic modulus was $24.4 \pm 21.0$ N/mm$^2$ for the IL, $22.4 \pm 21.1$ N/mm$^2$ for the IS and $24.9 \pm 30.8$ N/mm$^2$ for the PF, any difference was non-significant (Fig. 2A; Table 2). Similar findings were observed for the maximum strain with $84.5 \pm 36.0\%$, $86.1 \pm 30.0\%$ and $72.43 \pm 33.21\%$ for the IL, IS and PF respectively with non-significant differences, (Fig. 2B). Ultimate stress averaged $10.0 \pm 7.6$, $7.7 \pm 6.9$ and $6.5 \pm 4.2$ N/mm$^2$ for the IL, IS and PF respectively, the differences were also non-significant (Fig. 2C).

#### 3.2. Gender and side comparisons tend to have lower elastic moduli and higher maximum strains in females compared to males

The elastic modulus of the IS was significantly lower in females than in males ($11.3 \pm 9.9$ vs. $28.5 \pm 23.3$ N/mm$^2$; $p=0.018$; Suppl. Fig. 1; Table 2). The maximum strain of the IS was significantly higher in females than in males ($110.0 \pm 43.8\%$ vs. $73.0 \pm 28.2\%$; $p=0.02$). Ultimate stress was not significantly different between females and males with $6.0 \pm 5.5$ and $8.7 \pm 7.5$ N/mm$^2$ respectively. No such gender differences were found for the IL and the PF. Moreover, the side-related differences did not reach a statistically significant level.

#### 3.3. Significant alterations were found for the mechanical properties of the ilio- and pubofemoral ligaments between younger and older specimens

The averaged values from both sides were compared between the tissues of a young group (< 55 years, $n=15$) and that of an old group ($\geq 55$ years). A significant difference was found for the maximum strain between the young group with $120.0 \pm 25.0\%$ and the older group with $60.0 \pm 50.0\%$, $p=0.018$. Other mechanical properties did not significantly differ between the age groups.

![Fig. 2. Box plots of the mechanical properties obtained from the ilio-, ischio- and pubofemoral ligaments, (A) Elastic modulus, (B) Ultimate stress, (C) Maximum strain. Whiskers indicate the 25th and 75th percentile, black rectangles indicate the outliers.](image-url)
Table 2
Gender- and side-dependent elastic modulus, maximum strain and ultimate stress data are given for the ligaments of the hip joint capsule along with the global data averaging the data of the ligaments. SD = standard deviation.

<table>
<thead>
<tr>
<th>Ligament</th>
<th>Gender</th>
<th>Side</th>
<th>Elastic modulus Mean ± SD</th>
<th>Ultimate Stress Mean ± SD</th>
<th>Maximum Strain Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean ± SD</td>
<td>SD</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>Iliofemoral</td>
<td>♂</td>
<td>left</td>
<td>29.01 ± 26.09</td>
<td>11.05 ± 9.58</td>
<td>8.82 ± 4.90</td>
</tr>
<tr>
<td></td>
<td>♂</td>
<td>right</td>
<td>19.57 ± 13.74</td>
<td>9.97 ± 7.64</td>
<td>9.50 ± 4.90</td>
</tr>
<tr>
<td></td>
<td>♂</td>
<td></td>
<td>24.44 ± 20.95</td>
<td>6.02 ± 5.52</td>
<td>5.90 ± 4.90</td>
</tr>
<tr>
<td></td>
<td>♂</td>
<td></td>
<td>11.33 ± 9.93</td>
<td>6.86 ± 7.52</td>
<td>5.90 ± 4.90</td>
</tr>
<tr>
<td>Ischiofemoral</td>
<td>♀</td>
<td>left</td>
<td>28.52 ± 23.31</td>
<td>8.66 ± 7.52</td>
<td>5.90 ± 4.90</td>
</tr>
<tr>
<td></td>
<td>♀</td>
<td>right</td>
<td>28.45 ± 26.28</td>
<td>9.63 ± 7.44</td>
<td>5.90 ± 4.90</td>
</tr>
<tr>
<td></td>
<td>♀</td>
<td></td>
<td>16.77 ± 13.36</td>
<td>7.72 ± 6.90</td>
<td>5.90 ± 4.90</td>
</tr>
<tr>
<td></td>
<td>♀</td>
<td></td>
<td>22.42 ± 21.14</td>
<td>7.72 ± 6.90</td>
<td>5.90 ± 4.90</td>
</tr>
<tr>
<td>Pubofemoral</td>
<td>♂</td>
<td>left</td>
<td>26.67 ± 34.88</td>
<td>5.48 ± 3.35</td>
<td>3.48 ± 2.35</td>
</tr>
<tr>
<td></td>
<td>♂</td>
<td>right</td>
<td>23.66 ± 28.43</td>
<td>7.26 ± 6.62</td>
<td>5.48 ± 3.35</td>
</tr>
<tr>
<td></td>
<td>♂</td>
<td></td>
<td>24.92 ± 30.77</td>
<td>6.51 ± 4.17</td>
<td>3.48 ± 2.35</td>
</tr>
</tbody>
</table>

Fig. 3. Maximum strain (black line) vs. dislocation distance (gray dashed line) for the iliofemoral ligament (IL), ischiofemoral ligament (IS) and pubofemoral ligament (PF). (A) Females and (B) males with 0° external rotation for all ligaments, (C) Females and (D) males at an external rotation of 30° for the IL, 45° for the IS and 0° for the PF. IL and IS maximum strain exceeded the dislocation distance in females without external rotation and in both genders with external rotation, and always at the 7 to 1 o’clock position.
group (≥ 55 years, n = 16). The elastic modulus was higher in the young group than in the old group for the IL (310 ± 22.5 vs. 183 ± 17.9 N/mm²) and the IS (274 ± 24.8 vs. 171 ± 15.4 N/mm²). However, these differences were not significant (p > 0.05). PF elastic modulus was significantly higher in the young compared to the old with 35.9 ± 39.1 vs. 13.3 ± 10.7 N/mm² (p = 0.02) respectively. Similarly ultimate stress was higher in the young than in the old for the IL (13.1 ± 9.1% vs. 71 ± 4.7%), the IS (8.0 ± 7.0% vs. 7.4 ± 7.0%), and the PF (7.7 ± 4.7% vs. 5.3 ± 3.2%), however the differences were non-significant (p > 0.05). Conversely, maximum strain of the IL was non-significantly lower in the young (810 ± 22.7 vs. 878 ± 45.7 N/mm²) and significantly lower for the IS (70.9 ± 26.5 vs. 102.2 ± 42.1 N/mm²; p = 0.02) and the PF (60.3 ± 21.2 vs. 85.4 ± 39.1 N/mm²; p = 0.05). Correlation analyses over the entire sample did not reveal any significant dependencies between the mechanical data and age, body weight or height.

3.4. Capsular ligament stiffness exceeds the threshold necessary for dislocation in females at 0° hip joint external rotation, and in both females and males at 30° and 45° external rotation

Comparison of IL, IS and PF maximum strain vs. the distance required for hip joint dislocation revealed gender- and angle-dependent results (Fig. 3). Without hip joint external rotation (0°), the IL and IS maximum strain exceeded the dislocation distance at the 6 to 1 o’clock position in females (Fig. 3A), but not in males (Fig. 3B). Calculations with the hip joint rotated externally showed that at angles of 30° and 45° the magnitude of potential dislocation increased to where the maximum strain exceeded the dislocation distance in females (Fig. 3C). The same effects were observed in males at these angles and at the same positions (Fig. 3D).

4. Discussion

The ligaments of the human hip joint are considered to be major mechanical stabilizers preventing dislocation. Hip joint stability relies upon the complex interplay between the bony congruency of the acetabulum and femur, the suction seal, the dynamic muscular forces, as well as capsular and ligamentous restraints (Myers et al., 2011; Smith et al., 2014). The surrounding muscles are known to be powerful limiters of dislocation (Heller et al., 2005). A number of different experimental setups have been utilized to examine hip joint ligament mechanical properties of the human hip joint ligaments mechanically using fresh (Hewitt et al., 2001, 2002; Ito et al. 2009; Smith et al., 2014; Stewart et al., 2002; Telleria et al., 2011), formaldehyde-fixed (Lohe et al., 1996) or ethanol-glycerin-fixed tissues (Pieroh, 2016). However, given the lack of standardization it is difficult to compare these data. Hewitt et al. found higher values for the elastic modulus of the IL (76 to 286 N/mm²) and the IS (81 to 100 N/mm²) in the samples from ten cadavers aged 50 years or older (Hewitt et al., 2001, 2002). Similarly, Stewart et al. reported mean elastic moduli of the entire capsule ranging between 110 and 186 N/mm² in their samples from five cadavers aged 68 years or older (Stewart et al., 2002). Such high elastic moduli could neither be found for the entire population ranging between 14 and 93 years, nor for the sample older than 50 years. The maximum strain and ultimate stress of the IS and IS obtained by Hewitt et al. were much lower than in our experiments (Hewitt et al., 2001, 2002), indicating that their samples may not have been tested perpendicular to the main fiber orientation. Comparison to our previous experiments with ethanol-glycerin fixed and rinsed samples (Pieroh, 2016), showed that elastic modulus increased, whereas maximum strain decreased. These results underline that ethanol-glycerin fixation causes irreversible changes in the soft tissues (Steinke et al., 2012), possibly by dehydration or proteoglycan washout. Previous reports on hip joint laxity being more predominant in females than in males (McCormick et al., 2014; Myers et al., 2011) can be confirmed by our results, especially in regards to the IS, revising the findings of our recent study (Pieroh, 2016).

4.2. There is evidence for the IS and PF to change age-dependently

It was been hypothesized that the hip joint ligaments undergo age-related changes in elasticity. The comparison between the two age groups (< 55 years and ≥ 55 years) revealed that there were significant decreases in PF elastic modulus, and significant increases in IS and PF maximum strain, providing evidence in favor of hypothesis II. However, no evidence for a linear change of IL, IS or PF elasticity could be found. Ageing is known to affect hip joint ligament mechanics (Frank et al., 1999; Fuss and Bacher, 1991; Hama et al., 1976; Helwig et al., 2013; Hewitt et al., 2001, 2002; Sato et al., 2012; Stewart et al., 2002; Ippolito et al. (1980) and Cotta (1961) found no changes in the collagen fibril diameter histologically and ultrastructurally in men. Moreover, comparison of the age-related changes of the hip joint ligaments to the changes occurring in the iliotibial tract are different (Hammer et al., 2012). The iliotibial tract undergoes age-related increases in stiffness (Hammer et al., 2012), whereas the hip joint ligaments appear to have decreased stiffness. The underlying mechanisms related to the changes leading to ligamentous loss of elasticity in the hip joint ligaments remains unclear.

4.3. The hip joint ligaments limit hip joint dislocation mechanically, but this mechanical restraint is minimized in external rotation

In a third hypothesis we investigated whether the hip joint ligaments may prevent dislocation passively due to an optimal ratio between ligament elasticity and length. Previously the mechanical properties of the IL and IS have been attributed to stabilizing effects (Elkins et al., 2011; Fessler, 1894; Fick, 1911). The IL being an important constraint of hip joint external rotation and anterior rotation (Myers et al., 2011). A recent study has shown that each of the capsular ligaments has a primary role in restraining hip joint rotation, exceeding the role of the ligamentum teres and the labrum as secondary constraints (van Arkel et al., 2015). The IL is known to have parallel-aligned collagen fiber bundles, whereas the IS consists of several layers including perpendicular orientations (Sato et al., 2012). Numerically it could be shown that the ligament stiffness-related dislocation-preventing
mechanism exists in males and in females at the attachment regions of the inferior IL and PF, preventing anterior and inferior hip joint dislocation in males at all times. However, the sites of the IS and the cranial attachments of the IL may not effectively prevent dislocation in females at 0°, and in both genders at 30° to 45° of external rotation. By using our numerical approach including mechanical data we could show that the spiral configuration of the hip joint ligaments may even facilitate hip joint dislocation, by unraveling around the joint space, creating more space (Domb et al., 2013). These results confirm the findings of Smith et al. (2014) that the IL, IS and PF appear to act independently to resist the end-range motion of the hip. Our results give strong evidence that there might be additional hip-stabilizing mechanisms that the hip joint ligaments might be involved in beyond mechanical stiffness. First, given the existence of mechanoreceptors such as Ruffini bodies, Golgi and Vater Pacini corpuscles within the capsular ligaments of the hip joint (Moraes et al., 2011), the transverse acetabular ligament (Lohe et al., 1996) and the teres ligament of the hip joint (Dehao et al., 2015; Leunig et al., 2000; Moraes et al., 2011; Muratli et al., 2004), these mechanoreceptors are likely part of neuromuscular feedback loops. These loops could terminate at the small external rotators of the hip, but also at the larger muscles such as the gluteus maximus and the iliopsoas. Additionally, the effects of atmospheric pressure onto the joint might be an important stabilizing factor (Fick, 1911; Prietzel et al., 2008, 2014b, 2007; Wingstrand and Wingstrand, 1997; Wingstrand et al., 1990). The extended strain caused by the atmospheric pressure results in an extended strain of the hip joint ligaments once dislocation begins, as it constantly presses the soft tissues towards the joint cavity. This consideration was intentionally disregarded in our numerical analysis to provide evidence towards additional (passive) phenomena providing hip joint stability.

5. Clinical implications

There is a wide consensus that the ligaments of the hip joint play a crucial role in stabilizing the hip joint (Benali and Katthagen, 2009; Domb et al., 2013; Elkins et al., 2011; Hewitt et al., 2001, 2002; Ito et al., 2009; Matsuda, 2009; Mei-Dan et al., 2012; Mihalko and Whiteside, 2004; Myers et al., 2011; Nepple and Smith, 2015; Ranawat et al., 2009; Shindle et al., 2006; Shu and Safran, 2011; Stewart et al., 2002; Tellier et al., 2011; Terry et al., 2006). These stabilizing effects are of particular interest in total hip arthroplasty, as capsular resection is well known to increase the risk of dislocation (Delgado et al., 2013; Gaulrapp and Zimmermann, 2000; Hewitt et al., 2002; Kerschbaumer et al., 2007; Nepple and Smith, 2015). A decreased hip joint stability was repeatedly reported following capsular incision or removal (Chiu et al., 2010; Domb et al., 2013; Kwon et al., 2006; Liebenberg and Domnissee, 1969; Myers et al., 2011; Prietzel et al., 2014a; Stewart et al., 2004). Surgical techniques at the hip joint have therefore evolved from mere removal of the ligaments in favor of reconstructing them surgically, which has been proven to be advantageous, both clinically (Domb et al., 2013; Prietzel et al., 2014a) and experimentally (Elkins et al., 2011; Hewitt et al., 2001, 2002; Stewart et al., 2004). The given study could show that the hip-joint-stabilizing effects of the capsular ligaments are unlikely to only be the result of ligament stiffness, but also of additional phenomena such as atmospheric pressure. These results have strong additional implications towards capsular reconstruction following total hip arthroplasty (Domb et al., 2013; Prietzel et al., 2014a). Further investigations are required to resolve the complex interplay of hip joint ligament elasticity, atmospheric pressure and neuromuscular loops.

6. Limitations

A number of limitations need to be addressed for this study. Larger sample sizes would have helped substantiate the differences, also to the effect of quantifying the observed differences to more extent. Cross-sections of the entire IL, IS and PF could not be evaluated from the samples provided, as this would have interfered with the measurement setup to obtain failure load data. Therefore comparisons between ligament lengths and dislocation distances were based on numerical estimations.

Conflict of interest statement

The authors have no conflict of interest related to this study.

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Appendix A. Supporting information

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