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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

Stefan Schleifenbaum [a,b,1], Torsten Prietzel [b,c,1], Carsten Hädrich [d], Robert Möbius [e], Freddy Sichting [f], Niels Hammer [a,*]

[a] Department of Anatomy, University of Otago, Dunedin, New Zealand
[b] Department of Orthopedics, Trauma and Plastic Surgery, University of Leipzig, Leipzig, Germany
[c] Department of Orthopedics and Trauma Surgery, HELIOS Clinic Blankenhain, Blankenhain, Germany
[d] Institute of Forensic Medicine, University of Leipzig, Germany
[e] Institute of Anatomy, University of Leipzig, Leipzig, Germany
[f] Institute of Sport Science, Department Human Locomotion, Chemnitz University of Technology, Chemnitz, Germany

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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/mm^2 (PF) respectively. Maximum strain was 84.5%, 86.1%, 72.4% and ultimate stress 10.0, 7.7 and 6.5 N/mm^2 for the IL, IS and PF respectively. None 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 ≥ 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.

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

* Correspondence to: Department of Anatomy, University of Otago, Lindo Ferguson Building, 270 Great King Street, Dunedin 9016, New Zealand. Fax: +64 3 479 7254.
E-mail address: nlshammer@googlemail.com (N. Hammer).
[1] These authors have contributed equally to this work.

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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 (I_A) and their side (I_B) as well as gender (I_C). 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.

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 Istra 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 $\nu = 20$ 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 $\nu = 20$ 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, Suwa, Japan) and determined using Measure 2.1d software (DatInf 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

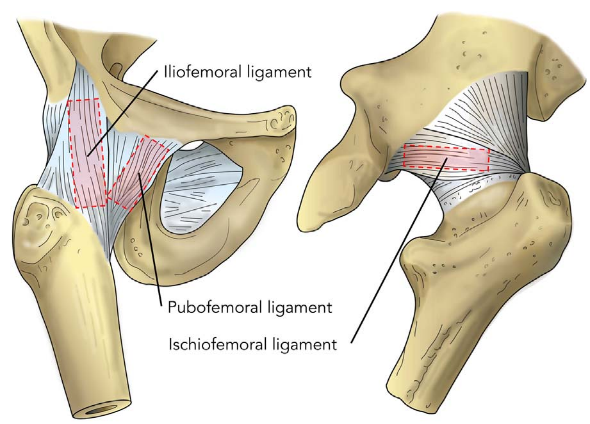

Fig. 1. The ligaments of the hip joint, anterior view (left) and posterior view (right). The red regions indicate where the respective ligaments were removed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Specimen data including gender, age, body height and weight and the cause of death.

Gender	Age [years]	Body length [cm]	Body weight [kg]	Cause of death
♀	14	154	44	Traumatic brain injury
♂	18	174	61	Unclear, non-traumatic
♂	20	178	65	Cervical spinal cord injury
♂	25	185	87	Traumatic hematothorax
♂	26	169	77	Peripheral vessel injury
♂	26	187	66	Heroin intoxication
♀	35	174	72	Unclear, non-traumatic
♂	41	177	56	Aspiration of foreign body
♂	51	175	65	Peripheral vessel injury
♂	53	183	91	Brain injury
♂	63	172	102	Traumatic hematothorax
♀	65	n/a	98	Hepatic tumor
♂	71	177	81	Cardiac insufficiency
♂	74	173	80	Myocardial infarction
♂	76	169	47	Septic shock
♀	77	158	68	Ethyl-toxic liver disease
♂	81	n/a	87	Mesenteric infarction
♀	81	n/a	56	Acute kidney failure
♀	87	n/a	62	Hepatic tumor
♀	90	n/a	84	Cardiac insufficiency
♀	93	n/a	54	Cardiac insufficiency
9 ♀, 12 ♂	59.7 ± 26.6	173.7 ± 8.9	70.0 ± 17.5	

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