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Validation of a six degree-of-freedom robotic system for hip *in vitro* biomechanical testing ☆

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ABSTRACT

Currently, there exists a need for a more thorough understanding of native hip joint kinematics to improve the understanding of pathological conditions, injury mechanisms, and surgical interventions. A biomechanical testing system able to accomplish multiple degree-of-freedom (DOF) movements is required to study the complex articulation of the hip joint. Therefore, the purpose of this study was to assess the repeatability and comparative accuracy of a 6 DOF robotic system as a testing platform for range of motion *in vitro* hip biomechanical analysis. Intact human cadaveric pelvises, complete with full femurs, were prepared, and a coordinate measuring machine collected measurements of pertinent femoral and pelvic bony landmarks used to define the anatomic hip axes. Passive flexion/extension path and simulated clinical exam kinematics were recorded using a 6 DOF robotic system. The results of this study demonstrate that the 6 DOF robotic system was able to identify hip passive paths in a highly repeatable manner (median RMS error of <0.1 mm and $<0.4°$), and the robotically simulated clinical exams were consistent and repeatable (rotational RMS error $\leq 0.8°$) in determining hip ranges of motion. Thus, a 6 DOF robotic system is a valuable and effective tool for range of motion *in vitro* hip biomechanical analysis.

1. Introduction

Currently, there is an incomplete understanding of the stabilizing function of the constituent elements of the hip joint (Bowman et al., 2010; Polkowski and Clohisy, 2010). This paucity of information has led to the design and development of numerous biomechanical testing platforms for the *in vitro* study of hip kinematics (Crawford et al., 2007; Smith et al., 2014). A more thorough understanding of native hip joint kinematics is essential for improving the understanding of pathological conditions, injury mechanisms, and surgical interventions and advancing hip rehabilitation. Robotic systems have been used for a variety of testing applications since they were first introduced into biomechanics orthopaedics research in the early 1990s (Fujie et al., 1996; Fujie et al., 1995; Fujie et al., 1993). Applications for the knee and shoulder have expanded the abilities of biomechanics research to quantitatively explore the native function and effects of surgical intervention on joint biomechanics through the use of serial or parallel robot manipulators (Atarod et al., 2014; Fujie et al., 2004; Goldsmith et al., 2013; Harner and Höher, 1998; Kennedy et al., 2013a; Mauro et al., 2008; Noble et al., 2010; Wijdicks et al., 2013a, b; Woo and Fisher, 2009; Zantop et al., 2004). Current hip biomechanics research has primarily been dominated by biomechanical testing systems that are unable to accomplish multiple degree-of-freedom (DOF) joint movements, which are essential for a full understanding of hip kinematics (Bay et al., 1997; Crawford et al., 2007; Dy et al., 2008; Ferguson et al., 2003; Ito et al., 2009; Nepple et al., 2014; Philippon et al., 2014). To better assess hip biomechanics during *in vitro* testing, a novel 6 DOF robotic/universal force-torque sensor testing platform has been developed for the hip. By extending previous robotic systems to the hip, we intend to facilitate and improve biomechanical testing of this complex joint.

The purpose of this study was to assess the repeatability and comparative accuracy of a 6 DOF robotic system during simulated range of motion clinical exams. Prior to *in vitro* testing, a robotic system must be validated (Darcy et al., 2009; Gilbertson et al., 1999; Goldsmith et al., 2014) to determine whether the system is an appropriate testing platform for hip biomechanical analysis and is able to simulate clinical hip exams. Therefore, this study aimed

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to first determine the repeatability of robotically generated passive flexion/extension paths. These flexion/extension positions served as the initial starting points for subsequent simulated clinical hip exams. Second, the repeatability and comparative accuracy of robotically applied range of motion (ROM) clinical exams were assessed. The comparative accuracy of the robotically simulated exam was assessed in relation to clinician-applied manual exams.

2. Method

2.1. Overview of robotic system

A KUKA KR 60-3 (KUKA Robotics Corp, Augsburg, Germany) robotic system was used in this study. The robotic system has been described and validated previously for knee joint testing (Goldsmith et al., 2014). The robotic system had a manufacturer reported maximum mass payload of 60 kg and position repeatability of $< \pm 0.06$ mm at maximum payload, reach, and speed. The six-axis universal force/torque sensor (UFS; Net F/T Delta IP65, ATI Industrial Automation, Apex, NC) attached to the robotic end effector had a manufacturer verified accuracy of $< 1.5\%$ of the full load.

2.2. Specimen preparation

Three fresh-frozen human cadaveric pelvises complete with intact femurs, knees, and proximal tibiae and fibulae (mean age: 48, range: 35–57; mean body mass index: 25.9, range: 20.3–32.9) and devoid of hip or knee injury or surgery were included in this study. Institutional review board (IRB) approval was not required because de-identified human cadaveric specimens are exempt from review at our institution. Specimens were stored at -20°C and thawed at room temperature for approximately 48 h prior to testing. All soft tissues, except for sacroiliac ligaments, pubic symphysis, hip capsular ligaments, and intra-articular structures, were dissected and removed from the pelvis, sacrum, and proximal femurs. Notably, the soft tissue of the knee was left intact for manual exam manipulation (Fig. 1A).

2.3. Robotic testing setup

A hip joint coordinate system was defined for each specimen to permit reporting of translations and rotations with respect to hip anatomic axes (Wu et al., 2002). A portable coordinate measuring machine (7315 Romer Absolute Arm, Hexagon Metrology, North Kingstown, RI) with a manufacturer's reported point repeatability (Single Point Articulation Test) of 0.025 mm was used to collect the 3D coordinates of pertinent femoral and pelvic bony landmarks based on the ISB (International Society of Biomechanics) standards for the femur, pelvis, and hip (Fig. 1B) (Wu et al., 2002). In brief, the hip joint center was defined from a best-fit sphere describing locations collected on the femoral head surface with the capsule intact. Pilot testing demonstrated that measurements collected with the capsule intact produced similar locations for the hip joint center compared to when the capsule was completely excised. Intraobserver and interobserver reliability for anatomic landmark identification was assessed for triplicate measurements by three independent investigators (M.T.R., C.A.C.T., and S.L.).

2.4. Hip neutral orientation alignment

Hip neutral orientation was determined by aligning the superior–inferior, medial–lateral, and anterior–posterior axes of the femoral and pelvic coordinate frames. Prior to alignment, the pelvis was transected along a transverse plane defined by the left and right anterior and posterior superior iliac spines. The sacroiliac joint was then disarticulated, and the hemi-pelvis was potted in poly(methyl methacrylate) (PMMA, Fricke Dental International Inc., Streamwood, Illinois, USA).

Next, the potted hemi-pelvis was rigidly mounted to maintain its position during femoral manipulation. Custom software (MATLAB R2014a, MathWorks, Natick, MA, USA) provided contemporaneous feedback of the femoral position, which was recorded using the coordinate measurement machine, and enabled precise, computer-guided, manual alignment of the superior–inferior, medial–lateral, and anterior–posterior axes of the femoral and pelvic coordinate frames (Wu et al.,2002). This femur-pelvis relationship was measured and used to generate the neutrally aligned hip coordinate frame.

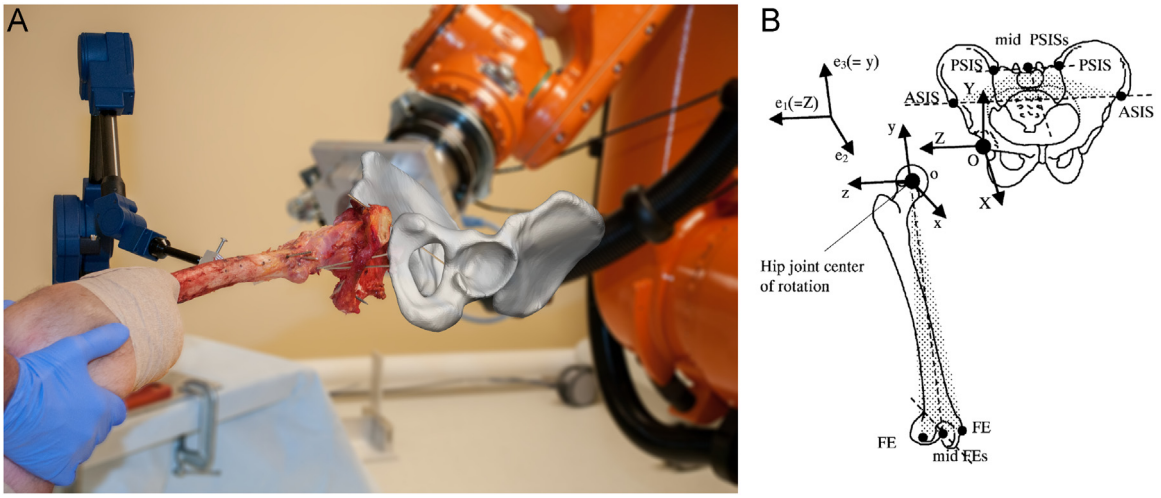

Fig. 1. Manual manipulation of the hip joint to locate neutral orientation. (A) The potted hemi-pelvis was held stationary while real-time femoral position and orientation information was output by a coordinate measuring machine to enable precise, computer-guided, manual manipulation of the femur into neutral hip alignment. A virtual reconstruction of the full pelvis is superimposed to aid visualization of pelvis landmarks collected prior to potting. (B) Neutral orientation of the hip coordinate frame was obtained by aligning the pelvis and femur coordinate frames according to the ISB standard for the hip joint. [Wu et al. Journal of Biomechanics 35 (2002) 543–548].

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2.5. Manually applied exam

The comparative accuracy of the robotically simulated exam was assessed in relation to a manual clinical exam applied to the right hip of a single cadaver. Clinically, a physician-applied physical hip examination is one of the primary assessment tools for detecting the abnormal ROM associated with hip pathology; therefore, the robotically obtained ROMs were compared to those obtained by manual manipulation. During manual hip manipulation, the coordinate measuring machine stylus (MicroScribe-MX with 6 DOF, GoMeasure3D, Amherst, VA; with a single point articulation test result of 0.08 mm) was rigidly affixed to the proximal femur to continuously measure the hip position and orientation during the manual exams (Fig. 1A). Three experienced orthopaedic surgeons (C.A.C.T., S.L., and J.N.) first articulated the hip three times through its passive flexion/extension path. After identifying the hip's passive path, simulated clinical exams (external rotation [ER], internal rotation [IR], abduction [ABD], and adduction [ADD]) (Martin et al., 2010) were manually applied three times to the hip at 0°, 30°, 60°, and 90° of hip flexion until bony or soft tissue constraints impeded further joint motion. In addition, combined rotation (ABD+ER and ADD+IR) experiments, which represented modified versions of the clinical FABER and FADIR exams (Martin et al.,2010), were performed by each physician throughout hip flexion. A goniometer was used to set the initial flexion angle prior to femoral manipulation. Each examiner was instructed to preserve neutral hip orientation in the non-examined dimensions (e.g. 0° of ABD/ADD during IR) and to stop when a distinct bony or soft tissue end point was achieved.

2.6. Passive flexion/extension path repeatability

Following neutral orientation alignment and manual examination, the femur was transected 15 cm distal to the greater trochanter, potted in PMMA, and mounted via a custom fixture to a six-axis universal force-torque sensor (Net F/T Delta IP65, ATI Industrial Automation, Apex, NC) attached to the end effector of the 6 DOF robot (Fig. 2). The potted hemi-pelvis was rigidly mounted to a static pedestal via a custom fixture.

Passive flexion/extension path testing was performed on two matched-pairs of hemi-pelvises (4 total). Experiments were performed with the center of the femoral head as the virtual tool center point. Translations (mm), rotations (°), forces (N), and torques (N-m) were recorded in the hip coordinate frame. Prior to initiating a simulated clinical exam, the hip's passive flexion/extension path positions and orientations were recorded while moving from 10° of extension to 100° of flexion in 1° increments. Throughout passive path testing, 10 N compressive forces (Smith et al., 2014) were applied axially and medially into the joint to ensure contact and proper anatomic alignment between the femoral head and acetabulum, similar to the compression force used in robotic knee testing (Goldsmith et al., 2013; Goldsmith et al., 2014; Kennedy et al., 2014a,b; Kennedy et al., 2013; Wijdicks et al., 2013a,b). At each flexion/extension angle, positions which met the minimization of forces and torques criteria (<5 N and <0.5 N-m, respectively) in the remaining DOFs were selected as locations comprising the hip joint's passive paths. The passive flexion/extension path established zero-force locations at defined flexion/extension angles, and these defined locations served as the start points for subsequent ROM testing. Passive flexion/extension path repeatability was calculated as the root-mean-square (RMS) error between three sequentially calculated passive paths utilizing the same neutral alignment starting position. Passive paths were completed in triplicate while the abduction/adduction joint orientation was preserved in neutral alignment under position control.

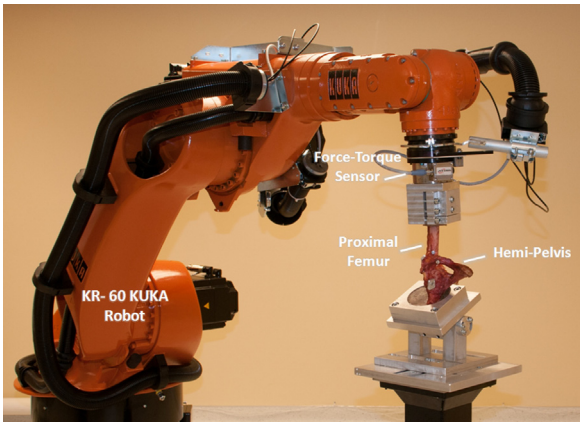

Fig. 2. Robotic system setup for a right human cadaveric hip. The femur was potted in poly(methyl methacrylate) (PMMA) and mounted in a custom fixture attached to a force/torque sensor attached to the end effector of a KUKA KR-60 robot. The pelvis was potted in PMMA and rigidly attached with a custom fixture to a static pedestal. Hip capsular and intra-articular structures were retained during the testing procedure.

2.7. Range of motion (ROM) testing

Passive flexion/extension path positions served as the starting points for the subsequent simulation of ROM testing. Hip ROM was assessed for IR, ER, ABD, and ADD with a 5 N-m torque (Myers et al., 2011). A 5 N-m torque was selected and based off of prior literature (Myers et al., 2011; Smith et al., 2014) and pilot testing results, which showed minimal differences in rotation when the applied torque exceeded 4 N-m. During each exam, the flexion angle was preserved while translations were permitted in the remaining DOFs. Additional rotations were restricted so that the hip joint's neutral orientation was preserved at each tested flexion angle (IR/ER neutral orientation preserved during ABD/ADD tests and ABD/ADD neutral orientation preserved during IR/ER tests). Combined rotation (ABD+ER and ADD+IR) experiments, which represent modified versions of the clinical FABER and FADIR exams, were also performed with the two 5 N-m rotations applied either step-wise or simultaneously. Repeatability of ROM testing was calculated at each tested flexion angle as the RMS error for three repeated trials. The manually applied clinical exam at each tested flexion angle was related to the robotically applied simulated clinical exam in order to assess comparative accuracy during ROM testing. The use of a prescribed set of applied forces in the hip's anatomic axes for a force control based hip manipulation offered a diagnostic method for repeatable ROM assessments. For our system, a forward kinematics approach, by reproducing manually generated motions with the robotic system, was not implemented since this approach may limit future testing methods to healthy hips because subsequent injured or repaired hip states may be unable to achieve the same intact hip ROM.

2.8. Statistical analysis

To determine the intraobserver and interobserver repeatability for hip tool selection based on palpable anatomic landmarks, the intraobserver repeatability (RMS error) was calculated from each repetition's difference from the observer's average. Interobserver repeatability was calculated as the RMS error of each observer's first trial compared to the interobserver average.

To determine system repeatability of the calculated passive flexion/extension path, a centroid path was calculated for each tested specimen from the three passive path repetitions. At each flexion angle, the error between each repetition and the centroid

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was used as error in the RMS error calculations. The maximum and median RMS error was calculated when grouping errors across flexion angles and specimens. Similarly, for the simulated clinical exams, the average of the three repetitions was used to generate RMS error values for the simulated exams. The maximum RMS error was calculated across the specimens and the total RMS error was calculated by grouping across the specimens.

3. Results

3.1. Hip joint coordinate frame repeatability

For all collected anatomical landmarks, the intraobserver repeatability RMS error was 1.4 mm and interobserver repeatability was 4.0 mm. The most inconsistently identified points were the medial epicondyle and the posterior superior iliac spine. The femoral head center had an average intraobserver repeatability of 0.6 mm and an interobserver repeatability of 1.3 mm. Resultant hip coordinate frames were consistently placed with an RMS error of 1.2 mm and 1.8 mm for intraobserver and interobserver repeatability, respectively, for the coordinate frame origin. Coordinate frame orientation agreed between observers to within 3° for all dimensions. A single hip joint coordinate frame was calculated and used for all subsequent validation testing.

3.2. Robotically simulated exams

Robotically simulated clinical exams were consistently repeatable in determining hip ROM (Table 1). External rotation exams ranged from an average rotation of 26.5° at 0° of flexion to 43.7° at 90° of flexion, with a maximum ER RMS error of 1.1° for repeatedly accomplishing the exam. Internal rotation ranged from 26.5° at 90° of flexion to 35.8° at 30° of flexion with a maximum IR RMS error of 1.2° for repeatedly accomplishing the exam. The ABD during the robotically simulated exam ranged from 37.7° to 62.1° at 0° and 90° of flexion, respectively, while ADD resulted in small 7.1° ADD rotations at 0° of flexion and a maximum of 32.8° at 60° of flexion. The maximum RMS error for the abduction and adduction exams was 1.1° and 0.6°, respectively.

Combined robotic rotational tests resulted in substantial rotations at all tested flexion angles. The simulated AB+ER exam resulted in 14.6–43.9° of ER and 25.8–68.1° of ABD with a maximum RMS error of 1.7°. The simulated AD+IR exam resulted in 8.3–28.5° of IR and 1.8–28.1° of ADD with a maximum RMS error of 2.8°. Substantial changes were observed depending on the flexion angle of application and the method of application (stepwise versus simultaneous). Larger rotations were accomplished with the AB+ER exam compared to the AD+IR exam, and the AB+ER exam showed more consistency with smaller maximum RMS error values observed.

3.3. Comparison to manual exam

Hip ROM was compared between the manual and robotic examinations, which both aimed to determine the end point of rotation for a single hip specimen. Manually applied clinical exams resulted in larger variability than the robotically applied exams. The maximum and median intraobserver RMS error was 5.7° and 1.6° for ER, 5.6° and 1.5° for IR, 2.6° and 1.0° for ABD, and 2.5° and 1.1° for ADD. When comparing between surgeons, the maximum interobserver RMS error was 15.6° for ER, 6.3° for IR, 6.7° for ABD, and 5.3° for ADD. Comparable rotations were observed between robotic and manual examination of hip ROM (Fig. 4).

3.4. Passive flexion/extension path repeatability

During preliminary testing, passive path analysis demonstrated a substantial increase in variability, with differences of $>5°$ in the ABD/ADD dimension at the end of flexion when comparing between the three repeated trials, when the ABD/ADD dimension was allowed to move freely in response to observed forces (Fig. 3). Abduction/adduction was therefore constrained to the neutral position during passive path collection. Rotational error for the flexion/extension and abduction/adduction dimensions remained consistent, with a maximum RMS error $<0.2°$ for both dimensions. Variability was observed within the internal/external dimension, where maximum RMS error was observed as 3.00° and median RMS error was 0.38°, with larger errors observed at higher flexion angles ($\geq 60°$). Three collections of each hip's passive path generated a consistent femoral head position (Table 2) with a maximum spatial RMS error of 0.46 mm and a median error of 0.07 mm.

4. Discussion

The most important finding of this study was the validation of a 6 DOF robotic system for repeatable evaluation of hip passive path and ROM clinical exams. While current biomechanical research frequently utilizes 6 DOF robotic systems to assess knee joint kinematics in human cadaveric specimens, these robotic systems have seldom been applied to the more complex hip joint. The development of a validated 6 DOF hip robotic testing system will

Table 1
Resultant rotations and range of motion during robotically simulated clinical hip exam.

Simulated exam		0° of flexion			30° of flexion			60° of flexion			90° of flexion		
		Avg (°)	RMS error (°)	Max RMS error (°)	Avg (°)	RMS error (°)	Max RMS error (°)	Avg (°)	RMS error (°)	Max RMS error (°)	Avg (°)	RMS error (°)	Max RMS error (°)
ABD		37.7	0.7	1.1	50.2	0.4	0.5	56.9	0.3	0.4	62.1	0.3	0.5
ADD		7.1	0.2	0.3	25.1	0.3	0.5	33.6	0.4	0.6	26.8	0.3	0.5
ER		26.5	0.3	0.5	36.4	0.2	0.3	40.0	0.2	0.3	43.7	0.3	0.5
IR		27.7	0.8	1.2	35.8	0.6	0.9	35.7	0.4	0.5	26.5	0.4	0.5
ABER	*ER*	44.5	0.3	0.4	32.5	0.1	0.2	19.8	0.1	0.2	14.6	0.1	0.2
(Step-wise)	*ABD*	42.4	1.1	1.7	68.1	0.6	0.7	68.0	0.5	0.7	62.4	0.6	1.1
ABER	*ER*	37.2	0.3	0.5	43.9	0.1	0.2	27.3	0.1	0.2	23.4	0.3	0.4
(Simultaneous)	*ABD*	25.8	0.3	0.5	52.4	0.4	0.7	67.6	0.5	0.7	53.7	0.4	0.6
ADIR	*IR*	26.8	0.7	0.8	24.7	0.7	1.0	18.6	0.9	1.3	8.3	0.3	0.4
(Step-wise)	*ADD*	3.7	0.3	0.4	26.1	0.2	0.3	33.1	1.1	2.0	27.0	0.2	0.4
ADIR	*IR*	27.3	0.7	1.0	28.5	0.5	0.7	25.2	1.4	2.8	13.7	0.4	0.6
(Simultaneous)	*ADD*	1.8	1.2	2.4	20.9	0.1	0.2	28.1	1.2	2.3	24.3	0.2	0.3

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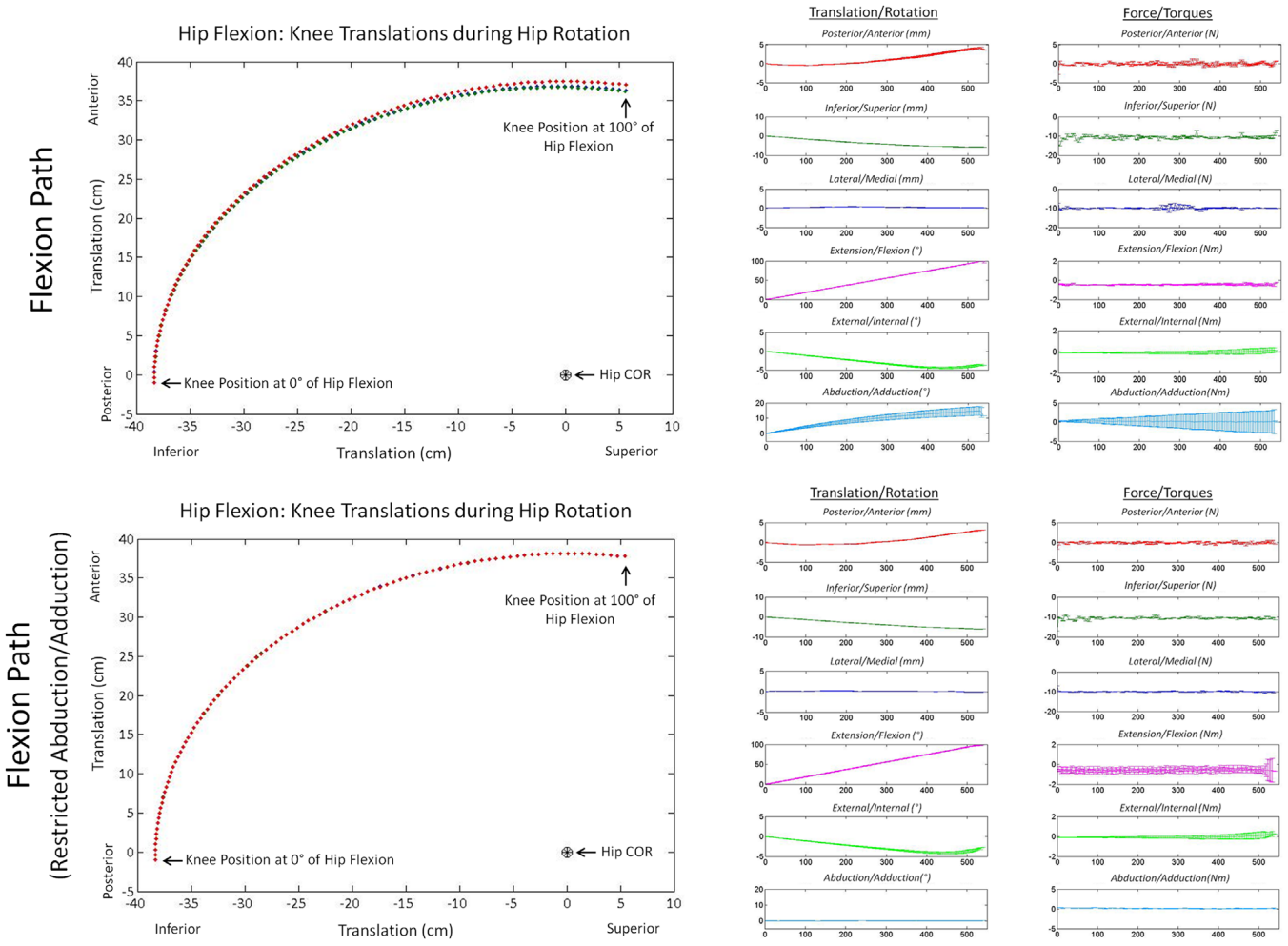

Fig. 3. Visualization of the robotically collected hip passive flexion paths. Passive flexion paths ($N=3$) were collected with 5 DOF (top) or 4 DOF (bottom, abduction/adduction restricted). Knee positions are used for the visualization of the hip passive flexion path (left). Hip translations and rotations with accompanying observed forces and torques are also visualized during the passive flexion path collection (right).

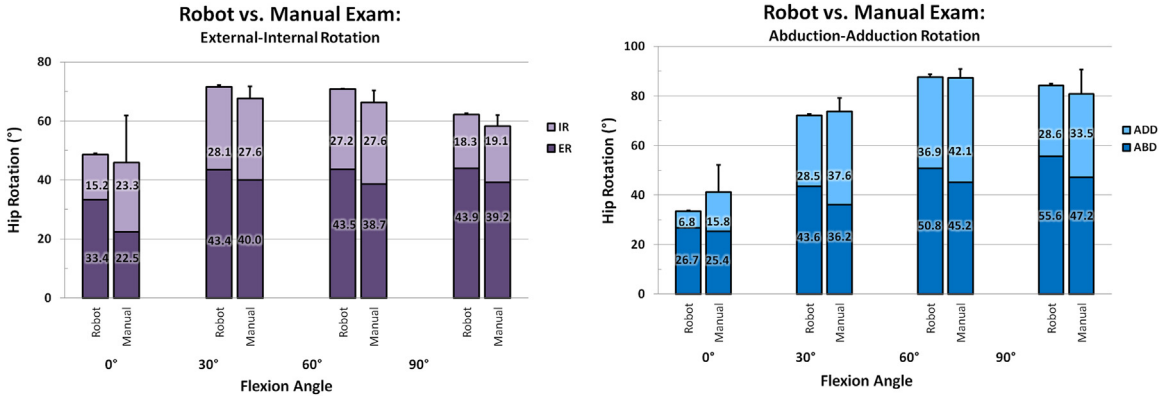

Fig. 4. Hip range of motion for external–internal rotation (left) and abduction–adduction (right) compared between robotically and manually applied hip exams for the same hip specimen. Graphs display the average rotation identified at each flexion angle. Error bars represent the standard deviation between the three repetitions of the robotic system or between the three exams manually applied by three surgeons.

lead to an improved understanding of the biomechanical role of hip structures and testing of surgical procedures to repair or reconstruct hip pathology.

This study demonstrates that the simulation of hip exams by a robotic system represents a vast improvement in system repeatability compared to manual exam. In our study, robotic hip manipulation resulted in an order of magnitude of improved test repeatability compared to either intraobserver or interobserver repeatability during manual exam. An accurate and repeatable system is necessary to observe the small differences resulting from changes in the hip joint, such as those found in sequential sectioning studies. Additionally, tensile testing machines have been

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Table 2
Robotic flexion/extension passive path repeatability.

Dimension	Specimen 1 (Left hip) RMS error Median/max	Specimen 1 (Right hip) RMS error Median/max	Specimen 2 (Left hip) RMS error Median/max	Specimen 2 (Right hip) RMS error Median/max	Average RMS error Median/max
Spatial error (mm)	0.20/0.38	0.11/0.46	0.06/0.08	0.10/0.12	0.07/0.46
Flexion–extension (°)	0.04/0.16	0.02/0.05	0.01/0.01	0.01/0.01	0.01/0.16
Internal–external (°)	0.79/1.53	0.59/3.00	0.24/0.39	0.64/1.01	0.38/3.00
Abduction–adduction (°)	0.04/0.17	0.01/0.02	0.01/0.04	0.00/0.01	0.01/0.17

previously used to answer clinically relevant questions for the hip (Bay et al., 1997; Crawford et al., 2007; Dy et al., 2008; Ferguson et al., 2003; Ito et al., 2009; Nepple et al., 2014; Philippon et al., 2014), but remain unable to achieve complex motion patterns essential for testing the hip ball-and-socket joint. The combination of system accuracy and repeatability with the ability to generate complex 3D movement patterns makes a robotic system an effective tool for analyzing the hip.

In addition to developing a repeatable robotic testing clinical methodology, it was important to assess whether the robotically simulated exams adequately replicated physician-applied clinical exams. Experienced orthopaedic surgeons simulated hip clinical examinations through internal, external, abduction, and adduction rotations, which permitted direct comparison between the physician- and robotically-obtained ROMs. The full internal/external and abduction/adduction ROMs were similar between both the manually and robotically applied clinical examinations. However, slight differences existed for some individual rotation exams, which may be attributed to different start point orientations during the manual exams; the orthopaedic surgeons displayed initial variability in the abduction/adduction and external/internal orientation at each flexion angle start point of the clinical examinations. These differences could arise from difficulties when attempting to manually maintain neutral rotation during the exams, since some movements in the hip joint are coupled. For example, an average of 6° and 8° of unintended ER resulted when abducting and adducting the hip at 90° of flexion. For this study, pure one-axis rotations were desired for more reliable comparisons between the ROM limits obtained by the robotic system and clinicians.

Another focus of this study was to assess the robotic system's repeatability for identifying the hip's passive path, since these passive path locations represent the start points for all subsequent ROM testing. Initially, the ABD/ADD dimension was permitted to change in response to observed forces during manipulation of the femur, but this resulted in considerable passive path variability. Previous literature reported intraclass correlation coefficients for interobserver reliability in determining flexion and extension amongst experts using visual estimates with moderate (ICC=0.55) and substantial (ICC=0.64) agreement, respectively (Chevillotte et al., 2009). The mean absolute difference between two observations of passive ROM for two experienced surgeons was 3.9° (±4.81°) for flexion and 0° (±0°) for extension (Chevillotte et al., 2009). The authors concluded that visual estimates for ROM are inaccurate and that a more consistent and repeatable method is needed for assessing passive hip ROM. Use of a goniometer or electromagnetic tracking system (ETS) in assessing ROM reportedly improves ICC test-retest reliability drastically (flexion ICC=0.916 for goniometer and ICC=0.943 for ETS) (Nussbaumer et al., 2010). Still, the standard error of measurements for the goniometer and ETS were 3.94° and 2.96°, respectively (Nussbaumer et al., 2010). In our study, we were able to analyze the RMS error of the entire robotically generated passive flexion/extension path and observed median RMS error values less than 1°, which is well below that of the previously mentioned manual methods.

In an additional study investigating hip ROM, Myers et al. (2011) made a general estimate of their system repeatability by twice testing ER and IR, separated by 30 min, at each flexion angle. They found the largest difference between their repeated tests was 0.8° for ER and 0.7° for IR. By comparison, the largest RMS error observed for our testing system was 0.3° for ER and 0.8° for IR across all specimens and flexion angles. Although our results are comparable to the study by Myers et al., our repeat testing is not simply delayed by time, but also incorporates a complete cycle of ROM testing between each repeat test.

In order to assess the implications of our observed variability, we can compare our robotic system to previously reported repeatability values for alternative robotic testing systems. Smith et al. (2014) reported a value of 0.2 mm for position and 0.2° for orientation repeatability for their Puma system, while Darcy et al. (2009) report a value of 0.3 mm for position and 0.1° for orientation repeatability for their FANUC system and 0.1 mm and 0.1° orientation repeatability for their KUKA system. These experimentally obtained repeatability measurements are comparable to the values previously found for the KUKA system used in our investigation (Goldsmith et al., 2014). Unfortunately, purely reporting a system's position and orientation repeatability does not accurately describe the system's repeatability for more complex movement patterns, including the ability to repeatedly move between points or a series of passive path points, both of which have been previously shown to result in significantly higher repeatability values and resultant changes in joint forces (Darcy et al., 2009; Goldsmith et al., 2014). By reporting the expected variability resulting from repeated calculation of the passive path or repeated application of torques, our paper aims to provide a more practical assessment of variability which would be useful for determining the system's contribution to observed error during joint testing. To that end, median and mean RMS rotational errors consistently below 1.5° represents sufficient repeatability, especially when compared to the high inter- and intra-variability observed during manual exams. The observed repeatability during robotically applied ROM exams is likely below the surgeons' sensitivity threshold when manually performing the exams and likely represents a negligible contribution of variability to experimental simulation of clinical ROM exams but should nonetheless be taken into account when planning future studies.

Nevertheless, the hip ROMs obtained in this study for both robotic and manual exam testing were similar to those reported previously (Bedi et al., 2011; Chevillotte et al., 2009). Moreover, the increased focus on evaluating treatments of hip pathology, such as femoroacetabular impingement (FAI) and capsular injury, has stimulated the need for a reliable assessment tool. However, it is important to note that *in vivo* assessments of ROM utilize announcement of pain as the end-point, whereas a robotic system can only identify the limits of motion as a result of bony impingement or soft tissue restraint. The finding that the robotic system

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had RMS error values $\leq 0.8^\circ$ for the internal, external, abduction, and adduction exams demonstrates its ability to assess small differences that may arise as a result of surgical treatment.

All hip exams were applied to a theoretical tool representing the hip coordinate system as seen at the femur. Our hip coordinate system was based on manually identifiable landmarks and the spherical femoral head's geometrical center. Although the femoral head surface might be best identified via full joint exposure, we elected to preserve the capsular ligament integrity. This decision was based on a finding by Crawford et al. (2007) which reported that a small injury, such as venting of the joint, resulted in increased ER and ABD of 1.5° and 1.9°, respectively. However, alternative methods for identifying landmarks or calculating the functional hip center of rotation may further improve the accuracy and repeatability of the robotically simulated exams compared to the non-invasive method for identifying the hip coordinate frame employed by this study. We encourage future studies to build upon and identify improvements to the methodology presented here to better assess hip kinematics.

Despite the improved robotic system testing methodology, this study acknowledges the presence of some limitations. With a limited number of specimens for determining exam repeatability, the hip ROM resulting from our robotically simulated exam may not fully reflect the observed clinical exam ROM for an anatomically diverse population. Additionally, the specimen age and gender (all male) may result in a different population than observed clinically. Future studies should further explore the effect of anatomic variability on reported hip ROM. Furthermore, the specimens were tested with their native bony, capsular, and intra-articular conditions. A group representing an injured sample was not tested as this study aimed to first perform the validation on normal hips. Manual clinical exam results were limited by the coordinate measuring machine accuracy. Additionally, without the traditional endpoint of pain, the surgeons may have generated increased variability in their exam application than may be seen with a patient. Aside from the aforementioned limitations, some experimental design considerations could affect the interpretation of our results. In order to describe the kinematics relative to each specimen's unique anatomic axes, a standardized method for determining the axes needed to be identified. Thus, neutral alignment was determined by aligning the medial–lateral, superior–inferior, and anterior–posterior axes of the femur and pelvis based on the ISB standard (Wu et al., 2002). However, this method of alignment did not account for natural variations in pelvic tilt, incidence, or obliquity that may be observed within a normal population. By imposing this pelvic alignment on a specimen, we could be using, as a reference, an orientation that is not natural to the tested specimen. This presents an intrinsic limitation of using cadaveric specimens and further research should examine the range of variability observed for pelvic orientation during neutral weight-bearing stance within a normal population. Due to payload limitations for our robotic system, loading conditions for activities of daily living (such as walking, running, jumping/landing) that require many multiples of body weight applied to the joint could not be generated. We encourage future studies to expand upon our findings and investigate the simulation of such movements.

In summary, our results validate the use of a 6 DOF robotic system as a testing platform for range of motion *in vitro* hip biomechanical analysis. The robotic system demonstrated high repeatability during manipulation and good accuracy when compared to the ROM obtained with the manual exam. We anticipate the results of this study will provide an effective means for further determination of native hip biomechanical properties and evaluation of the effect of hip joint pathology and surgical interventions during robotically applied ROM exams.

Conflict of interest

The Steadman Philippon Research Institute and Smith & Nephew provided funding support for this research. CAW is currently an employee of Arthrex, but was not employed by Arthrex during his primary contribution to this study. RFL is a paid consultant for Arthrex, Ossur, and Smith & Nephew. CACT received funding from the Instituto Brasil de Tecnologias da Saude. MJP receives support from Smith & Nephew, MIS, Arthrosurface, DonJoy, Slack, Linvatec, and HIPCO. Author affiliations did not present any conflicts of interest relevant to the preparation or presentation of this manuscript. Smith & Nephew had no role in performing the study or manuscript preparation.

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References

Atarod, M., Rosvold, J.M., Frank, C.B., Shrive, N.G., 2014. A novel testing platform for assessing knee joint mechanics: a parallel robotic system combined with an instrumented spatial linkage. Ann. Biomed. Eng. 42, 1121–1132.

Bay, B.K., Hamel, A.J., Olson, S.A., Sharkey, N.A., 1997. Statically equivalent load and support conditions produce different hip joint contact pressures and periacetabular strains. J. Biomech. 30, 193–196.

Bedi, A., Dolan, M., Hetsroni, I., Magennis, E., Lipman, J., Buly, R., Kelly, B.T., 2011. Surgical treatment of femoroacetabular impingement improves hip kinematics: a computer-assisted model. Am. J. Sports Med. 39, S43–S49, Suppl..

Bowman Jr., K.F., Fox, J., Sekiya, J.K., 2010. A clinically relevant review of hip biomechanics. Arthrosc.: J. Arthrosc. Related Surg. 26, 1118–1129.

Chevillotte, C.J., Ali, M.H., Trousdale, R.T., Pagnano, M.W., 2009. Variability in hip range of motion on clinical examination. J. Arthroplast. 24, 693–697.

Crawford, M.J., Dy, C.J., Alexander, J.W., Thompson, M., Schroder, S.J., Vega, C.E., Patel, R.V., Miller, A.R., McCarthy, J.C., Lowe, W.R., Noble, P.C., 2007. The 2007 Frank Stinchfield Award. The biomechanics of the hip labrum and the stability of the hip. Clin. Orthop. Related Res. 465, 16–22.

Darcy, S.P., Gil, J.E., Woo, S.L.Y., Debski, R.E., 2009. The importance of position and path repeatability on force at the knee during six-DOF joint motion. Med. Eng. Phys. 31, 553–557.

Dy, C.J., Thompson, M.T., Crawford, M.J., Alexander, J.W., McCarthy, J.C., Noble, P.C., 2008. Tensile strain in the anterior part of the acetabular labrum during provocative maneuvering of the normal hip. J. Bone Joint Surg. Am. 90, 1464–1472.

Ferguson, S.J., Bryant, J.T., Ganz, R., Ito, K., 2003. An in vitro investigation of the acetabular labral seal in hip joint mechanics. J. Biomech. 36, 171–178.

Fujie, H., Livesay, G.A., Fujita, M., Woo, S.L.Y., 1996. Forces and moments in six-DOF at the human knee joint: Mathematical description for control. J. Biomech. 29, 1577–1585.

Fujie, H., Livesay, G.A., Woo, S.L., Kashiwaguchi, S., Blomstrom, G., 1995. The use of a universal force-moment sensor to determine in-situ forces in ligaments: a new methodology. J. Biomech. Eng. 117, 1–7.

Fujie, H., Mabuchi, K., Woo, S.L., Livesay, G.A., Arai, S., Tsukamoto, Y., 1993. The use of robotics technology to study human joint kinematics: a new methodology. J. Biomech. Eng. 115, 211–217.

Fujie, H., Sekito, T., Orita, A., 2004. A novel robotic system for joint biomechanical tests: application to the human knee joint. J. Biomech. Eng. 126, 54–61.

Gilbertson, L.G., Doehring, T.C., Livesay, G.A., Rudy, T.W., Kang, J.D., Woo, S.L.Y., 1999. Improvement of accuracy in a high-capacity, six degree-of-freedom load cell: application to robotic testing of musculoskeletal joints. Ann. Biomed. Eng. 27, 839–843.

Goldsmith, M.T., Jansson, K.S., Smith, S.D., Engebretsen, L., LaPrade, R.F., Wijdicks, C. A., 2013. Biomechanical comparison of anatomic single- and double-bundle anterior cruciate ligament reconstructions: an in vitro study. Am. J. Sports Med. 41, 1595–1604.

Goldsmith, M.T., Smith, S.D., Jansson, K.S., LaPrade, R.F., Wijdicks, C.A., 2014. Characterization of robotic system passive path repeatability during specimen removal and reinstallation for in vitro knee joint testing. Med. Eng. Phys. 36, 1331–1337.

Harner, C.D., Höher, J., 1998. Evaluation and treatment of posterior cruciate liagement injuries. Am. J. Sports Med. 26, 471–482.

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Ito, H., Song, Y., Lindsey, D.P., Safran, M.R., Giori, N.J., 2009. The proximal hip joint capsule and the zona orbicularis contribute to hip joint stability in distraction. J. Orthop. Res. 27, 989–995.

Kennedy, N.I., LaPrade, R.F., Goldsmith, M.T., Faucett, S.C., Rasmussen, M.T., Coatney, G.A., Engebretsen, L., Wijdicks, C.A., 2014a. Posterior cruciate ligament graft fixation angles, part 1: biomechanical evaluation for anatomic single-bundle reconstruction. Am. J. Sports Med. 42, 2338–2345.

Kennedy, N.I., LaPrade, R.F., Goldsmith, M.T., Faucett, S.C., Rasmussen, M.T., Coatney, G.A., Engebretsen, L., Wijdicks, C.A., 2014b. Posterior cruciate ligament graft fixation angles, part 2: biomechanical evaluation for anatomic double-bundle reconstruction. Am. J. Sports Med. 42, 2346–2355.

Kennedy, N.I., Wijdicks, C.A., Goldsmith, M.T., Michalski, M.P., Devitt, B.M., Aroen, A., Engebretsen, L., Laprade, R.F., 2013. Kinematic analysis of the posterior cruciate ligament, part 1: the individual and collective function of the anterolateral and posteromedial bundles. Am. J. Sports Med. 41, 2828–2838.

Martin, H.D., Kelly, B.T., Leunig, M., Philippon, M.J., Clohisy, J.C., Martin, R.L., Sekiya, J.K., Pietrobon, R., Mohtadi, N.G., Sampson, T.G., Safran, M.R., 2010. The pattern and technique in the clinical evaluation of the adult hip: the common physical examination tests of hip specialists. Arthroscopy 26, 161–172.

Mauro, C.S., Sekiya, J.K., Stabile, K.J., Haemmerle, M.J., Harner, C.D., 2008. Double-bundle PCL and posterolateral corner reconstruction components are codominant. Clin. Orthop. Relat. Res. 466, 2247–2254.

Myers, C.A., Register, B.C., Lertwanich, P., Ejnisman, L., Pennington, W.W., Giphart, J. E., LaPrade, R.F., Philippon, M.J., 2011. Role of the acetabular labrum and the iliofemoral ligament in hip stability: an in vitro biplane fluoroscopy study. Am. J. Sports Med. 39, S85–S91, Suppl..

Nepple, J.J., Philippon, M.J., Campbell, K.J., Dornan, G.J., Jansson, K.S., LaPrade, R.F., Wijdicks, C.A., 2014. The hip fluid seal–Part II: The effect of an acetabular labral tear, repair, resection, and reconstruction on hip stability to distraction. Knee Surg. Sports Traumatol. Arthrosc. 22, 730–736.

Noble Jr., L.D., Colbrunn, R.W., Lee, D.G., van den Bogert, A.J., Davis, B.L., 2010. Design and validation of a general purpose robotic testing system for musculoskeletal applications. J. Biomech. Eng. 132, 025001.

Nussbaumer, S., Leunig, M., Glatthorn, J.F., Stauffacher, S., Gerber, H., Maffiuletti, N. A., 2010. Validity and test-retest reliability of manual goniometers for measuring passive hip range of motion in femoroacetabular impingement patients. BMC Musculoskelet. Disord. 11, 194.

Philippon, M.J., Nepple, J.J., Campbell, K.J., Dornan, G.J., Jansson, K.S., LaPrade, R.F., Wijdicks, C.A., 2014. The hip fluid seal – Part I: the effect of an acetabular labral tear, repair, resection, and reconstruction on hip fluid pressurization. Knee Surg. Sports Traumatol. Arthrosc. 22, 722–729.

Polkowski, G.G., Clohisy, J.C., 2010. Hip biomechanics. Sports Med. Arthrosc. Rev. 18, 56–62.

Smith, M.V., Costic, R.S., Allaire, R., Schilling, P.L., Sekiya, J.K., 2014. A biomechanical analysis of the soft tissue and osseous constraints of the hip joint. Knee Surg. Sports Traumatol. Arthrosc. 22, 946–952.

Wijdicks, C.A., Kennedy, N.I., Goldsmith, M.T., Devitt, B.M., Michalski, M.P., Aroen, A., Engebretsen, L., Laprade, R.F., 2013a. Kinematic analysis of the posterior cruciate ligament, part 2: a comparison of anatomic single- versus double-bundle reconstruction. Am. J. Sports Med. 41, 2839–2848.

Wijdicks, C.A., Michalski, M.P., Rasmussen, M.T., Goldsmith, M.T., Kennedy, N.I., Lind, M., Engebretsen, L., Laprade, R.F., 2013b. Superficial medial collateral ligament anatomic augmented repair versus anatomic reconstruction: an in vitro biomechanical analysis. Am. J. Sports Med. 41, 2858–2866.

Woo, S.L., Fisher, M.B., 2009. Evaluation of knee stability with use of a robotic system. J. Bone Joint Surg. Am. 91 (Suppl. 1), S78–S84.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D'Lima, D.D., Cristofolini, L., Witte, H., Schmid, O., Stokes, I., 2002. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion–part I: ankle, hip, and spine. International Society of Biomechanics. J. Biomech. 35, 543–548.

Zantop, T., Lenschow, S., Lemburg, T., Weimann, A., Petersen, W., 2004. Soft-tissue graft fixation in posterior cruciate ligament reconstruction: evaluation of the effect of tibial insertion site on joint kinematics and in situ forces using a robotic/UFS testing system. Arch. Orthop. Trauma Surg. 124, 614–620.

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