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Original Article

Quantifying dog meniscal volume at 1.5T and 3.0T MRI

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Abstract

The dog has been used extensively as an experimental model to study meniscal treatments such as meniscectomy, meniscal repair and regeneration. Accurate quantification of meniscal size and morphology are a crucial step for developing models of the meniscus. 3.0T magnetic resonance imaging (MRI) has been found to be highly accurate in analyzing the meniscus in both clinical and research fields. However, 3.0T MRI systems are still uncommonly used in veterinary medicine. The goal of the study was to compare meniscal volume measurements from 1.5T MRI system with 3.0T MRI system using proton density sequence, a clinically relevant protocol. The MR images were segmented to reconstruct 3D surface representations of both medial and lateral menisci to compare the meniscal volumes measurements. Average volume differences were 8.8% ($P=0.42$) and 8.9% ($P=0.535$) for medial and lateral meniscus, respectively. No significant volume differences were found between 1.5T and 3.0T magnetic resonance (MR) measurements, with high Pearson's correlation coefficient of $r > 0.8$ and the intraclass correlation coefficient (ICC) of 0.899. For inter- and intra-observer reproducibility, high correlation (ICC = 0.942 and 0.814) was observed, but with high variability for intra-observer reproducibility (lower bound 0.478, upper bound 0.949). We have shown that common clinical MR scanners and pulse sequences can be used to quantify dogs' meniscal volumes with good reproducibility. We believe that repeatable measurements of meniscal volumes using MR may provide a useful capability for assessment of postoperative results following meniscal treatments such as meniscectomy and meniscal regeneration.

Keywords: Meniscus, MRI, Dog, Meniscal volume, Medial image segmentation

1. Introduction

The menisci of the knee are crescent-shaped structures that contribute to load distribution, lubrication, and stability of the tibiofemoral joint (Kurosawa et al., 1980; Mow and Huiskes, 2005; McDermott et al., 2008). Because of their unique morphology, the menisci improve congruity and provide greater articular contact area between the femoral and tibial condyles. The importance of the structure-function relationship of the knee meniscus has been demonstrated in experimental studies, guiding surgeons towards a conservative approach in treating meniscal injuries (Fithian et al., 1990).

Meniscal injury, repair, replacement and regeneration are topics of great interest to surgeons in both human and veterinary medical fields. Total meniscectomy is a treatment option that is rarely performed because of the direct relationship that has been demonstrated between loss of meniscal tissue and the development of osteoarthritis (Burr and Radin, 1982; Roos et al., 1998; Englund and Lohmander, 2004; Berjon et al., 1991). Meniscal repair is preferred when possible, but partial meniscectomy is still indicated when the meniscal tear cannot be sutured (Tudor et al., 2014; Thieman et al., 2010; Pozzi et al., 2010). In an attempt to restore meniscal function when repair is not possible, cell and tissue regenerative strategies have been investigated, mostly in experimental studies (Scotti et al., 2013). The ability to quantify meniscal volumes noninvasively permits acute study of surgical procedures (e.g. partial meniscectomy) and longitudinal studies of meniscal regeneration following novel treatments such as intra-articular mesenchymal stem cells (Vangsness et al., 2014).

Accurate quantification of meniscal size and morphology is a crucial step for developing models of the meniscus. Many finite element models have been developed to study the biomechanical contact behaviour of the knee joint. These models provide numerical solutions of stress distributions within tissues that cannot be readily measured in experimental models (Guo et al., 2014; Pena et al., 2005). Clinically, accurate meniscal volume measurements could assist in postoperative evaluations of different meniscal treatments like partial meniscectomy and reconstruction. Meniscal volume can be used as an evaluating factor for analyzing the growth, healing process, surgical outcome after treatment (Bowers et al., 2007, Scotti et al., 2013, Vangsness Jr et al., 2014). Previous studies have accurately measured the meniscal volumes for humans (in-vitro and in-vivo) with different imaging protocols and different magnetic resonance (MR) magnet strengths, with 3.0T magnetic resonance imaging (MRI) systems being most common (Blöcker et al., 2013; Bowers et al., 2007; Wirth et al., 2010; Siorpaes et al., 2012).

With the recent advances in 3.0T MRI systems offering significant advantages for musculoskeletal imaging (Craig et al., 2005; Kornaat et al., 2005; Magee, 2007; Mosher, 2006; Ramnath, 2006; Tanenbaum, 2006), the use of 3.0T MRI systems are becoming more common in clinical practice in human medicine. 3.0T MRI systems provide better signal-to-noise ratio in imaging ligament and cartilage tissues (Kornaat et al., 2005), as well as meniscal structures of the knee (Craig et al., 2005; Magee, 2007), and have excellent sensitivity and specificity for detecting meniscal tears (Magee and Williams, 2006; Ramnath et al., 2006). However, 1.5T MRI systems are still commonly used in veterinary medicine. There has been continued investigation comparing the uses of 1.5T and 3.0T MRI systems (Eckstein et al., 2005; Link et al., 2006; Soher et al., 2007), but to the best of our knowledge, no previous study has observed a direct comparison between meniscal volume measurements in dogs between 1.5T and 3.0T MRI systems.

The goal of this investigation was to determine if measurements of canine meniscal volume using a 1.5T MRI system were comparable to results using a 3.0T MRI system with similar common clinical protocols, a single proton density sequence, because 3.0T MRI systems are still uncommon in veterinary medicine. Stifles were imaged under a compressive load and in four different joint positions to simulate in vivo meniscal conditions. Stifles were imaged in both sagittal and dorsal planes. We hypothesized there would be no significant difference between the meniscal volume measurements from 1.5T and 3.0T MRI systems.

2. Materials and methods

2.1 Experimental Animals

IACUC# 20130788 was approved for this study involving 16 pairs of menisci (n=32), from 16 intact stifles from 16 medium breed dogs (range 20-35 Kg), euthanized for reasons unrelated to this study. Dogs were selected primarily for healthy joints and body weight, resulting in inclusion of four breeds. The skin and regional musculature were dissected and removed from the limbs. Both femur and tibia were sectioned 12 cm above and below the joint, to prepare each intact stifle with consistent lengths of femur and tibia. A transepicondylar k-wire was drilled through the femur and tibia under fluoroscopic guidance to allow mechanical loading and the k-wire was replaced with a carbon-fiber rod for MR compatibility.

2.2 Experimental Design

Prior to MR imaging, each stifle was placed into a non-metallic loading jig that provided a fixed flexion angle and applied a compressive load across the joint (Park et al., 2018). To approximate in vivo conditions of a 30kg dog in a standing position, a static axial load of 30% body weight (98N) was applied (Kim et al., 2009). The load was applied along the long axis of the tibia with two elastic bands on the medial and lateral aspects of the joint. The band displacement required to develop 49N tension was calibrated with a mechanical testing machine (MTS 858 miniBioniox®, MTS, Eden Prairie, MN) every time prior to set up. Stress-relaxation tests showed there was less than 2N variation in elastic band tension over a 30-minute test modelling the MR scan time. The stifles were placed at four different positions to simulate the full range of stifle flexion during daily activities: 35° flexion, 150° flexion, and 135° flexion with tibial internal and tibial external rotation. A ten-minute hold was observed after compressive load application to allow the specimens to reach equilibrium. MR imaging was then conducted with only a few minutes interval between each of the four poses during specimen repositioning. For the third and fourth joint poses, an additional elastic band was applied to the tibia with sufficient torque to achieve maximum internal and external rotation. Specimens were kept hydrated during the entire MR imaging process by wrapping them in wet towels once thawed.

2.3 MRI Protocols

Intact stifles were thawed prior to imaging in two freeze/thaw cycles. First 8 stifles scanned at 1.5T in the first thaw cycle (at University of Florida) and scanned at 3.0T in the second thaw cycle (at TexasA&M University), while the last 8 stifles were scanned at 3.0T in the first thaw cycle and 1.5T in the second thaw cycle. A quadrature knee coil was used for 1.5T MR imaging (Toshiba Titan, Toshiba, Duluth, Georgia, U.S.A) and a 15-channel transmit/receive coil was used for 3.0T MR imaging (Siemens Verio, Siemens, Malvern, Pennsylvania, USA). Based upon preliminary exams performed to obtain good quality images of the menisci, the 1.5T MR scans were performed using a proton density sequence (repetition time, 4300 milliseconds; echo time, 18 milliseconds; flip angle, 90°; field of view, 120 mm; matrix, 512x512, slice thickness/gap, 2 mm/0 mm), and the 3.0 T MR scans were performed using a similar proton density sequence (repetition time, 4210 milliseconds; echo time, 25 milliseconds; flip angle, 90°; field of view, 120 mm; matrix, 512x512, slice thickness/gap, 2 mm/0 mm) in both sagittal and dorsal planes. All images were stored on a picture archiving and communication system (PACS) in digital imaging and communications in medicine (DICOM) format.

2.4 Meniscal volume measurements

To calculate the meniscal volume using manual segmentation of MR images, an open-source software (ITK-SNAP, www.itksnap.org) (Yushkevich et al., 2006) was used to reconstruct 3D surface representations of the medial and lateral menisci (Fig. 1). Sixteen stifles at a single position were segmented two more times (total of three) by a single observer (at 6 months and 12 months later) to assess intra-observer reproducibility. An additional subgroup of 10 stifles at a single position were segmented by two other, highly trained (experience of more than 6 years) observers (three observers in total) to assess inter-observer reproducibility.

2.5 Statistical analysis

All measurements for significance were calculated using ANOVA with alpha of 0.05 (Miller Jr, 1997). The meniscal volume measurements at four different stifle positions from both 1.5T and 3.0T in sagittal and dorsal views were compared for significance using three-way ANOVA. Pearson's correlation coefficient (r) (Lawrence and Lin, 1989), Intraclass correlation coefficient (ICC) (Bartko, 1966), and Bland Altman limits of agreement were computed to assess agreement between the 1.5T and 3.0T volume measurements (Bland and Altman, 1986). Medial and lateral data were calculated separately. For intra and inter-observer reproducibility, one-way ANOVA was used to compare for significance, along with ICC for correlations. All statistical calculations were performed using IBM SPSS statistics software version 24 (IBM Corporation, Armonk, New York).

2.6 Results

The average medial meniscus volumes from 1.5T MR images were 341mm3 with standard deviation (SD) of 67mm3, and from 3.0T were 330mm3 with SD of 68mm3 (P=0.42) (Fig. 2). There were no statistical significant differences found using three-way ANOVA with observation measured between different MRI magnet strength (P=0.42), MRI views (sagittal/dorsal, P=0.069), and between different stifle positions (P=0.516). Medial meniscus volume measurements showed high correlation (ICCm=0.879 and r=0.816), with Bland Altman plot shown in Fig. 3. The overall mean bias ± SD for medial meniscus were 7.5mm3 ± 35 mm3. The volume measurements from 35FLX had the lowest mean bias of 4.1mm3 but had the highest SD of 45mm3 with 95% limits of agreement of -83mm3 and 91mm3. Results from EXT had the highest mean bias with the lowest SD of 14.4mm3 ± 27mm3. Mean bias and the 95% limits of agreement at 4 different stifle positions for the medial meniscus are shown in Table 2.

For lateral menisci, the average volumes were 505mm3 (SD 105mm3) and 473mm3 (SD 102mm3) for 1.5T and 3.0T MRI, respectively (Table 1). No statistically significant differences were found between volumes measured from 1.5T and 3.0T MR systems (P=0.535), at different stifle positions (P=0.518), or between MRI views (sagittal/ dorsal) (P=0.25). High correlations were also observed between 1.5T and 3.0T MRI volume measurements for the lateral meniscus (ICCl=0.899 and r=0.855). The overall mean bias ± SD for the lateral meniscus were 24.1 mm3 ± 45 mm3 (Table 3). The volume measurements from 150FLX stifle position had the lowest mean bias and SD of 17.7mm3 ± 39mm3. Results from INT had the highest mean bias and SD of 35.9mm3 ± 53mm3. Mean bias and the 95% limits of agreement at 4 different stifle positions for the lateral meniscus are shown in Table 3.

For intra-observer reproducibility, no statistical significant differences were found between 3 repeated measurement (P=0.982) with high correlation (ICC = 0.942, lower bound 0.866, upper bound 0.978). For inter-observer reproducibility between three observers, no statistical significant differences were found (P=0.209) with high correlation (ICC=.814), but with high variability when looking at lower (0.478) and upper bounds (0.949).

4. Discussion

Accurate measurements of meniscal volumes using MR may allow us to assess postoperative results following meniscal treatments in dogs (Arnoczky, 1999; Arnoczky and Warren, 1983). With the recent advances in MRI technology and techniques, the use of 3.0T MRI systems are becoming more common in human medicine. Previous reports suggest images from 3.0T MRI systems have significant clinical benefits compared to images from 1.5T MRI (Craig et al., 2005; Gold et al., 2004; Kornaat et al., 2005; Magee, 2007; Magee and Williams, 2006; Mosher, 2006; Ramnath, 2006; Ramnath et al., 2006; Tanenbaum, 2006), but how these different magnet strengths affect the measurement of canine meniscal volumes the 3D model reconstruction of the menisci from MR images are not known.

Because the use of 3.0T MRI systems is still not widespread in veterinary medicine, the objective of this study was to determine if measurements of meniscal volume using 1.5T MRI system were comparable to volumes using 3.0T systems with similar common clinical protocols. Since the ultimate goal of meniscal treatment is to restore the damaged or injured tissue to its normal function, the stifles were compressed during imaging to mimic weight-bearing conditions (Tremolada et al., 2014).

As expected, there were no statistically significant differences detected between the volumes measured from 1.5T and 3.0T MRI system for medial or lateral menisci. In addition, no statistically significant differences were detected for any protocol factors. We observed high correlations in meniscal volumes measured with 1.5T and 3.0T MRI for both medial and lateral menisci. The volume measurements from 1.5T MRI showed consistent over estimation when compared to 3T MRI for both medial and lateral meniscus. Overall mean bias was 7.5mm3 (1.8% of the total volume) and 24.1mm3 (4.9% of the total volume) for medial and lateral menisci, respectively. Intra-observer reproducibility was high with had high correlation (ICC=0.942). Inter-observer reproducibility had high correlation (ICC=0.814), but also high variability. This variability in the Intra-observer reproducibility was expected due to different experience levels of the observers. These results suggest the practical equivalence of 1.5T MRI for measuring meniscal volumes, and are comparable to results shown by Siorpaes et al in human knees (Siorpaes et al., 2012).

This study has several limitations. The largest limitation is the limited number of specimens with a total of 16 normal stifles. Also, we used standard imaging protocols to maintain clinical relevance, acknowledging high-resolution/high-contrast sequences may have provided different results. An additional limitation is that no water volume displacement tests of the menisci were done for volume accuracy assessment. Bowers et al. did previously show that highly accurate meniscal volume measurements could be obtained using 3.0T MRI systems (Bowers et al., 2007). Ideally, the stifles would have been imaged with both MR systems during the same freeze/thaw session. This was not done because the MRI systems were located at different institutions, necessitating multiple freeze/thaw cycles. All specimens underwent the same number of freeze thaw cycles and efforts were made always to keep the specimens hydrated, but the effect of thermal cycling on individual meniscal volumes is unknown.

5. Conclusion

This study has shown that 3D reconstructed meniscus volume measurements from 1.5T MRI are comparable to 3.0T MRI, with no statistical differences, high correlations, and good reproducibility between the measurements. The repeatable measurements of meniscal volumes using common veterinary clinical MRI systems may provide a useful capability for clinician in assessing postoperative results following meniscal treatments and in further meniscal research using 1.5T MRI system.

Conflict of interest statement

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

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Table 1

Average medial and lateral meniscal volume measurements with 1 standard deviation (SD) results.

	MRI	MRI View	Average Volume (mm^3)	SD (mm^3)
Medial	1.5T	SAG	349	69
		DOR	333	65
		Overall	342	67
	3T	SAG	343	65
		DOR	316	69
		Overall	329	68
Lateral	1.5T	SAG	520	106
		DOR	491	103
		Overall	506	105
	3T	SAG	490	105
		DOR	458	98
		Overall	474	102

Table 2

Bland Altman parameters for medial meniscus volume measurements between 1.5T and 3.0T MRI at four different stifle positions: 35° flexion (35FLX), 150° flexion (150FLX), and 135° flexion with tibial external (EXT) and tibial internal rotation (INT). The mean bias, standard deviation and the 95% limit of agreement are represented as measured volume (mm^3).

	Mean bias (mm^3)	Standard deviation (mm^3)	Lower 95% (mm^3)	Upper 95% (mm^3)
35FLX	4.1	45	-83	91
150FLX	6.8	30	-51	65
EXT	14.4	27	-37	66
INT	4.7	37	-66	78
Overall	7.5	35	-60	75

Table 3

Bland Altman parameters for lateral meniscus volume measurements between 1.5T and 3.0T MRI at four different stifle positions: 35° flexion (35FLX), 150° flexion (150FLX), and 135° flexion with tibial external (EXT) and tibial internal rotation (INT). The mean bias, standard deviation and the 95% limit of agreement are represented as measured volume (mm^3).

	Mean bias (mm^3)	Standard deviation (mm^3)	Lower 95% (mm^3)	Upper 95% (mm^3)
35FLX	17.7	42	-63	99
150FLX	17.7	39	-58	93
EXT	25.3	46	-62	113
INT	35.9	53	-65	137
Overall	24.1	45	-63	111

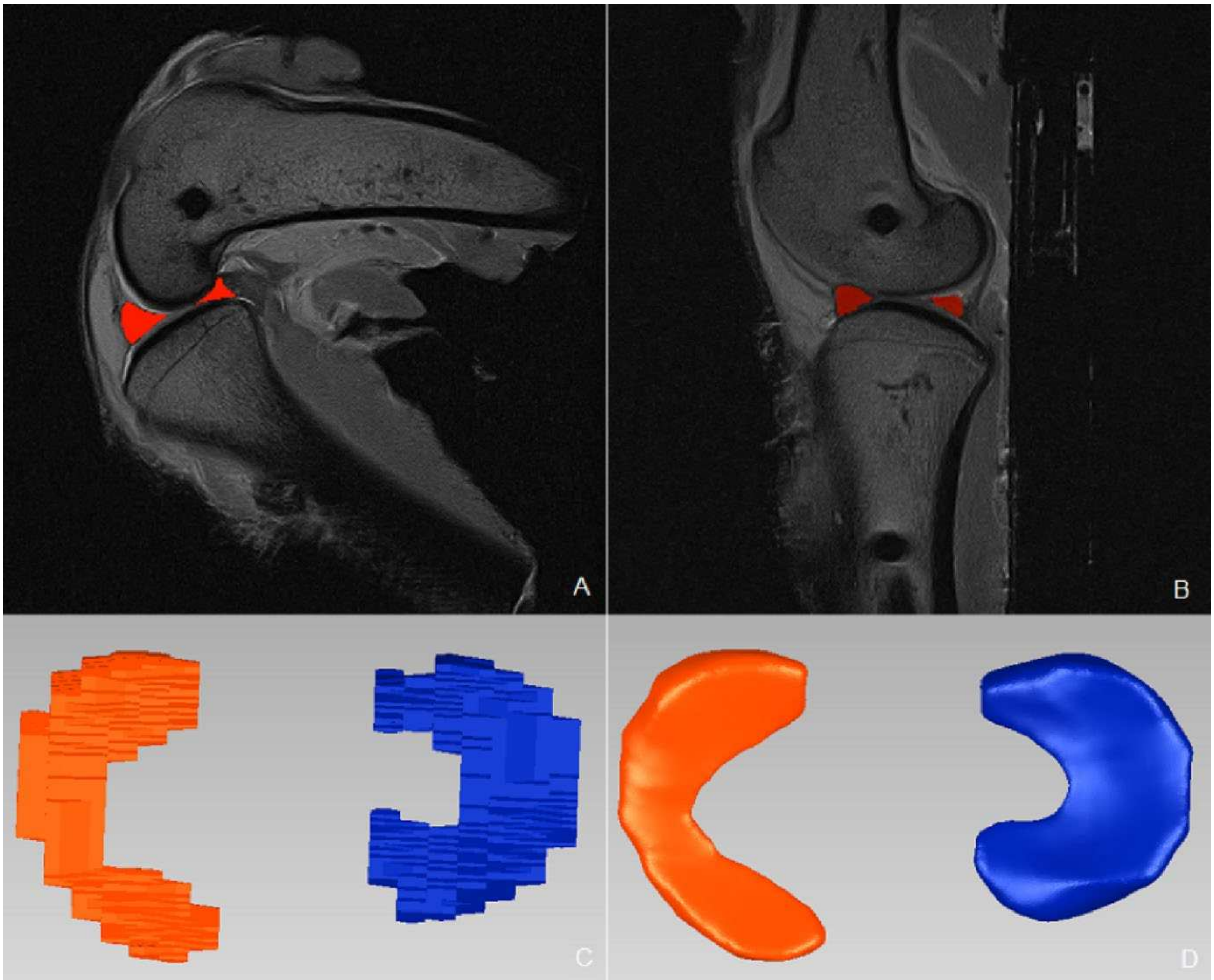

Fig. 1. MR images of the menisci and the resulting 3D meniscal models. MR image of an intact stifle at 35º flexion (A), an intact stifle at 150º flexion (B), an image of 3D meniscus model of the raw voxel (C), and smoothed (D).

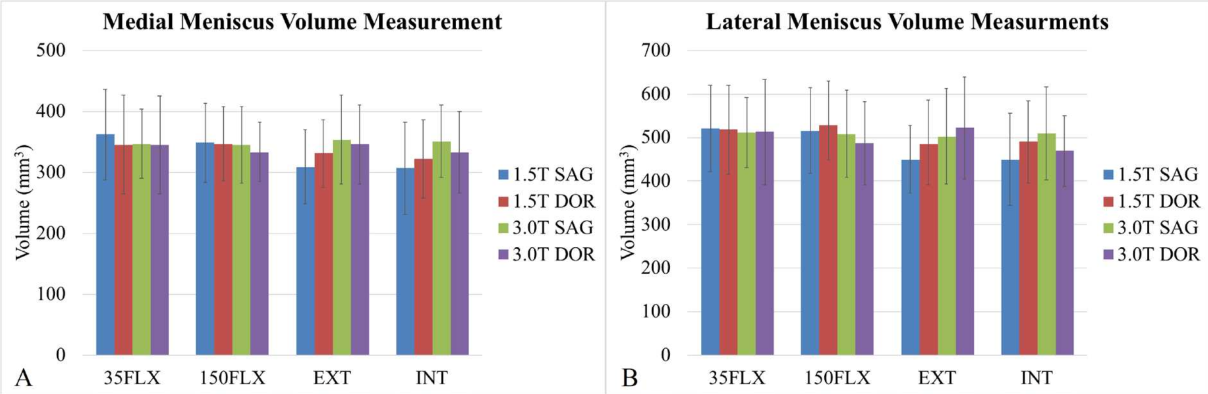

Fig. 2. Average mean (±1 standard deviation) medial (A) and lateral (B) meniscal volume measurements at 4 different stifle position: 35° flexion (35FLX), 150° flexion (150FLX), and 135° flexion with tibial external (EXT) and tibial internal rotation (INT).

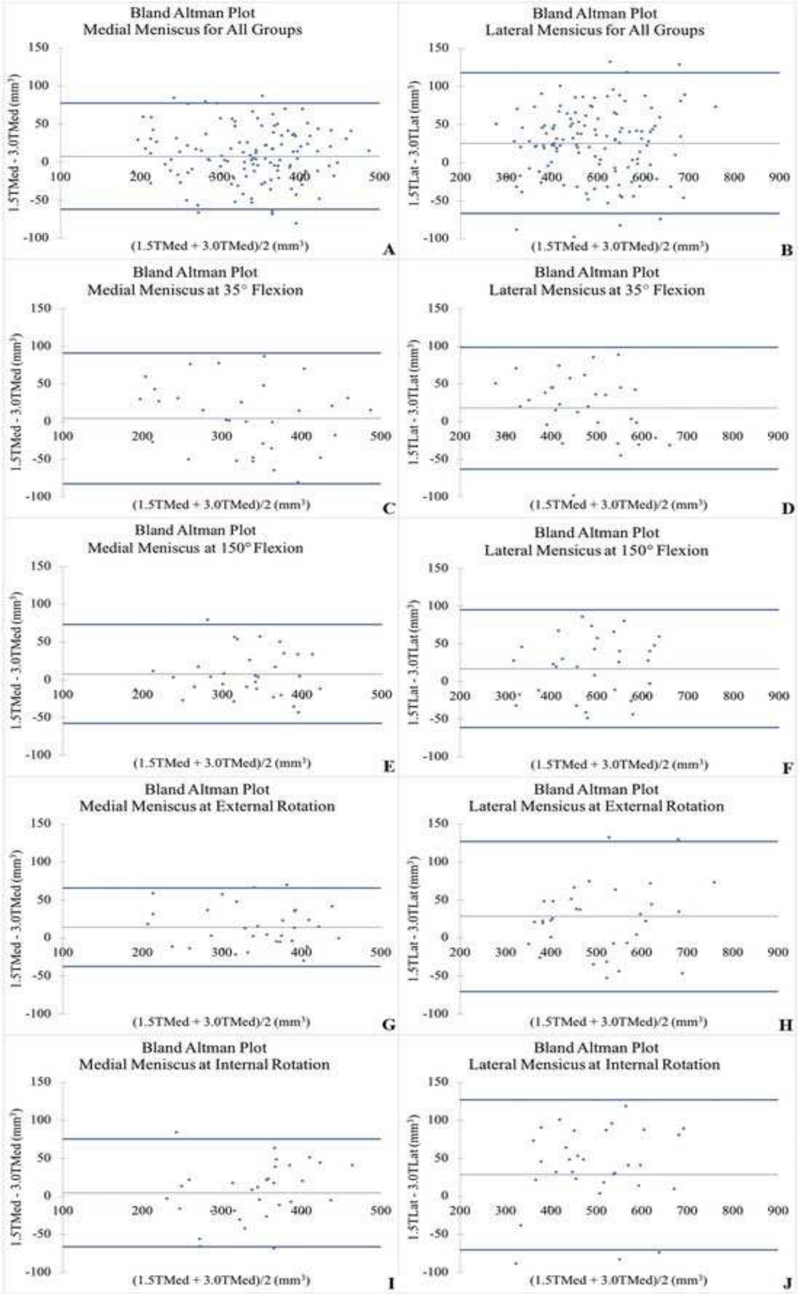

Fig. 3. Bland Altman plot for medial and lateral volume measurements. Bland Altman plots are displayed for separately for all groups (A,B) and at 4 different stifle position; 35° flexion (C,D), 150° flexion (E,F), tibial external rotation (G,H) and tibial internal rotation (I,J).