Evaluation of MRI images’ pixels intensity in three different MRI sequences

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Abstract. Numerous types of Magnetic Resonance Imaging (MRI) sequence have been utilized for in vivo tibiofemoral contact area study has led inconsistency and disproportionate results. Thus, this study aim is to assess intensity differences of MRI images in three different MRI sequences. Ten healthy subjects with average age of 25.5 ± 4.76 consisted three males and seven females have no history of knee injuries participated in this study. Subjects were scanned through an Achieva 3.0T TX coupled with a SENSE spine coil 15. The selected MRI sequences were Turbo Spin Echo (TSE), Fast Field Echo (FFE) and Steady State Free Precision (SSFP). The results showed that the SSFP sequence consistently uncovered extra contact areas than the FFE and TSE sequences. Overall intensity value indicated that the TSE sequence intersected the highest intensity differences at important knee tissue components: trabecular-cortical and cartilage-synovial. The study demonstrated that the TSE sequence yields an accurate contact length detection which promoted a consistent tibiofemoral contact area for quantification. Also, this study suggested that the TSE sequence is a proper MRI sequence selection for in vivo tibiofemoral contact area study.

1. Introduction

Disease and abnormality detections hold increasingly advantages through a one specific magnetic resonance imaging (MRI) sequence. As it continuously proven in recent studies, researchers were suggesting which MRI sequence suits best for a better detection of specific diseases and abnormalities [1], [2]. On the contrary measures taken under anthropometric study, in a distinctive practice, researchers exceptionally utilized various of MRI sequences differently one to another [3-8]. This spotty selection often pinned down one coherent drawback, such as anisometric result [8].

As a wholly agreed, to perceive in vivo tibiofemoral contact area, three key essential tissues mandatorily should appear in the MRI image; cartilage, menisci and synovial fluid [6]. The most important components for accuracy measurement of the tibiofemoral contact area are the clarity outlines and pixels cross-intensity value of those tissues. Yet, that is all depending on the right selection of MRI sequence and the right selection of coils being used [6], [9]. Should be noted that, the
more tissue outlines are clarified on the MRI images, the more intensity difference of those neighboring tissues could be attained, and the better the contact area analysis is conducted [10].

Through several reports that related to MRI selection specifically on knee, researchers suggested that the spin echo (SE) has a better detection of meniscal tear than the turbo/fast spin echo (TSE) [11], [12]. Meanwhile, on the similar study area, other journalists suggested the opposite [11], [13]. On the contact measurements, researchers mostly employed the automated segmentation [5], [8] and the customized algorithms [6], [14] for the quantification of tibiofemoral contact area. In principle, these quantification methods have an identical background operation. In a brief operation, the image processing software searches for spike binaries difference on the given coordinates [7]. The tibiofemoral contact area is then measurable by multiplications of tibiofemoral contact length and MRI images thickness based on the coordinates presented [6], [7].

Since the tibiofemoral contact area has a close related to in vivo knee contact pressure [15], [16], as well as a yardstick to gauge the knee arthroplasty kinematic [17], [18], it is important to ascertain the accurateness of in vivo tibiofemoral contact area. Thus, the aim of this study is to assess the intensity differences of MRI images in three different MRI sequences.

2. Materials and Methods
2.1. MRI Sequences and Intensity Analysis.

An Achieva 3.0T TX (Philips Healthcare, Eindhoven, Netherlands) the MRI scanner was used with a SENSE spine coil 15 placed on the MRI bed. Three subjects prior to this image intensity analysis test were conducted. All the subjects were consented and positioned in prone with both legs were fully extended and imaging under three MRI sequences; Turbo Spin Echo (TSE), Fast Field Echo (FFE) and Steady State Free Precision (SSFP). A two-dimensional (2D) of the MRI sequences was acquired for sagittal images, with a total of 34 slices each. The field of view (FOV) and the matrix sizes were set to have standard geometry for all three imagings, with 170 × 170 mm under 512 × 512 matrix. The image slice thickness and the gap between slices were standardized for each imaging at 2 mm and 0.2 mm, respectively. The echo time (TE), the repetitive time (TR) and the scanning time of each imaging resulted in an in-plane image resolution of 96 pixels per inch, or 0.27 mm per pixel. (Table 1).

| MRI sequence | Dimensional Space | TR (ms) | TE (ms) | Bandwidth (Hz) | Flip Angle (deg) | Scanning Time (s) |
|--------------|------------------|---------|---------|----------------|-----------------|-------------------|
| TSE          | 2D               | 4814    | 30.0    | 291.7          | 90              | 296.0             |
| FFE          | 2D               | 500     | 5.8     | 216.3          | 50              | 253.6             |
| SSFP         | 2D               | 623     | 12.0    | 216.8          | 20              | 346.5             |

TSE: Turbo Spin Echo, FFE: Fast Field Echo, SSFP: Steady State Free Precision, TR: Repetitive Time, TE: Echo Time

From the 34 slice images, one MRI image of respective slice of each sequence was selected for intensity measurement. The intensity measurement acquired from the MRI sequences were assisted using image processing toolbox and customized algorithm of Matlab software (Math-Works, Inc., Natick, MA). The algorithm extensively utilized improfile routine to create “U” lines profile across the bones and the tissues with a length of 3000 pixels (Fig. 1). Under properly declared of the algorithms, the intensity of the pixels was then presented in trends analysis.
2.2. **Volunteers and Contact Area Quantification.**

For tibiofemoral contact area quantification, ten healthy subjects with average age of 25.5 ± 4.76 which consisted of three males and seven females. All the subjects have been thoroughly checked to verify that no subjects have history of knee injuries participated in this study. The average weight and height for males were 68 ± 6.56 kg and 168.67 ± 4.16 cm, respectively. Meanwhile, the females had average weight and height of 51.43 ± 3.78 kg and 156.43 ± 3.99 cm, respectively. All the subjects were consented to the test procedure, which was approved by the Universiti Sains Malaysia Human Ethical Research Committee.

The subjects were scanned in three imaging positions using the TSE sequence. For the first imaging, each subject was positioned prone with fully extended knees (P1). Both subjects’ legs were held in place with leg-sponge supports to prevent motion. For the second imaging, the subjects were in prone position, but this time, a single knee was flexed at 140° (P2). For the last imaging, the subjects were placed in lateral decubitus position with a single knee flexed at 140° (P3). For the P2 and P3 positions, subjects’ knees were equipped with fabric wrappers and plastic goniometer which was fixed at the 140° flexion to prevent motion during imaging. Additional instruction was told which required subjects to relax their muscles and flex their knees normally, in order to avoid incongruity results formed between the subjects (Fig. 2).

On the post analysis, two types of contact area were investigated in this study; the first one was the contact area between the femoral cartilage and the tibial cartilage (C-T-C) and the second one was the contact area between the femoral cartilage and the meniscus (C-T-M). The contact lengths were identified using MATLAB software with the assistance of customized scripts. The algorithm worked by contrasting pixels in the MRI images and translated the MRI images into binary system. Instantly, the contact lengths were marked on the images between those cartilages and meniscus (Fig. 3). Detail configurations of the contact area calculations and the customized scripts were properly described in the previous research [7].

**Figure 1.** Lines profile on TSE sequence crosses trabecular, cortical, cartilage, anterior and posterior menisci for intensity measurement.
Figure 2. First position (a) subjects in prone with knees fully extended, P1. Second position (b) subjects in prone with knee flexed at 140°, P2, and the last (c) subjects in right decubitus with knee flexed at 140°, P3. (Note: for clarification purposes the images were taken outside the MRI bore.)

Figure 3. Plotted contact lengths on MRI images during (a) P1 position, (b) P2 position and (c) P3 position. Red and green pixels represented contact lengths for C-T-C and C-T-M, respectively.

2.3. Statistical Analysis
For statistical analysis, ANOVA statistical tests have been conducted to identify the significance difference of the all three tested MRI sequences. On the contact area quantifications, a two-tailed t-test was used to determine the significance differences covered in C-T-C and C-T-M at both medial and lateral compartments. Furthermore, ANOVA statistical test was engaged again to disclose the significance difference covered in the contact area at given subject positions. All the statistical analyses were used IBM SPSS statistic ver. 20 software (IBM Corp, Armonk, NY).

3. Results
The results showed fluctuation of intensity trends across trabecular, cortical, cartilages, menisci and synovial fluid (Fig. 4). The trabecular of femoral regions lie in two parts; anterior, (lines profile: 0 and 473) and posterior, (lines profile: 2732 and 3000). Whereas, the trabecular of tibial region rested between 832 and 2116 of the lines profile. On intensity comparison, other than cartilages and menisci, the rest of the tissues had the opposite intensity value to the TSE sequence. Furthermore, based on overall intensity value, the TSE sequence intersected the highest intensity differences at trabecular-cortical and cartilage-synovial (Fig. 5). Meanwhile, the SSFP sequence held the highest intensity differences in cartilage-meniscus, synovial-meniscus and cortical-cartilage. In contrast to the FFE sequence, the lowest intensity differences in cartilage-synovial, cartilage-meniscus and synovial-meniscus were found instead.
Figure 4. Image intensity of subject 1 under three different MRI sequences; turbo spin echo (TSE), steady state free precision (SSFP) and fast field echo (FFE).

Figure 5. Intensity differences of MRI sequences, between Trabecular-Cortical (Tra-Cor), Cortical-Cartilage (Cor-Car), Cartilage-Synovial (Car-Syn), Synovial-Meniscus (Syn-Men) and Cartilage-Meniscus (Car-Men).

On the contact area results, consistently, the SSFP sequence had extra contact areas than the FFE and TSE sequences (Fig. 6). From statistical analysis, between the three MRI sequences, C-T-C and C-T-M contact areas were found significance difference with $p < 0.05$. Furthermore, having the TSE sequence at all three positions; P1, P2 and P3. The contact area in medial compartment showed the C-T-C and C-T-M of P1 had average of $186.16 \pm 39.52$ mm$^2$ and $400.42 \pm 59.36$ mm$^2$, respectively (Fig. 7). At P2, the contact area of C-T-C and C-T-M abruptly decreased to the average of $82.65 \pm 51.87$ mm$^2$ and $210.29 \pm 45.72$ mm$^2$, respectively. The contact area then had a slight increase at P3,
with average of 108.90 ± 55.07 mm² and 274.21 ± 56.42 mm² for C-T-C and C-T-M, respectively. Statistically, C-T-C and C-T-M contact areas were significance difference in the all three positions, with p < 0.05.

In lateral compartment, the average contact area at P1 for C-T-C and C-T-M were 142.87 ± 43.28 mm² and 376.03 ± 99.64 mm², respectively. A sharp transition of C-T-C occurred at P2 and P3, with average of 70.23 ± 33.05 mm² and 50.06 ± 50.06 mm², respectively. Meanwhile, a slight inflection happened for the C-T-M at P2 and P3, with a small decreased to 206.06 ± 43.61 mm² and 216.43 ± 85.68 mm², respectively. On the one hand, statistically, C-T-C and C-T-M contact areas, resulted in significance difference at the all three positions, with p < 0.05. On the other hand, as further statistical analysis taking place in C-T-C and C-T-M, there were no significance difference found in P1 and P2, in both medial and lateral compartments. Not surprisingly, at P3, C-T-C contact area was found statistically significance difference with p = 0.026.

**Figure 6.** Average tibiofemoral contact area using SSFP, FFE and TSE sequences.

**Figure 7.** Contact areas in the medial and lateral compartments at position P1, P2 and P3 by using TSE sequence.
4. Discussion
A proper utilized of MRI sequences on a specific study has lots been highlighted of its advantages. Especially on the disease and abnormality detections, in usual exercise, researchers suggest one specific MRI sequence has a better outcome for a specific disease detection [1], [2]. Unlike tibiofemoral contact area, due to lack of consistency, enormous numbers of MRI sequences have been utilized for the same equivalent study [3–8] (Table 2). This spotty exercise upon MRI sequence selection, as literatures suggest would reside drawbacks such as inconsistency measurement and incomparable of tibiofemoral contact area [6], [7]. To appreciate the accuracy of tibiofemoral contact area, as an important component in the knee physical movement [3], as well as to improve knee arthroplasty kinematic understanding [19]. The aim of this study was to assess the intensity difference of MRI images in three different MRI sequences.

Three selected MRI sequences were tested: TSE, SSFP and FFE. Among those three, the SSFP sequence crossed the highest intensity differences between cartilage-meniscus, synovial-meniscus, and cortical-cartilage (Fig. 5). The SSFP sequence holds advantages as it more identifiable neighboring tissues visualized in the MRI images. Sequentially, the quantification of C-T-C contact area tend to be more consistent and reproducible under the SSFP sequence. However, the SSFP sequence created a very limited intensity difference specifically for cartilage-synovial (Fig. 6). In term of practicality to the tibiofemoral contact area analysis, this minimum intensity difference casted a major drawback to C-T-M quantification since the existence clarification of the cartilage prone to interchange with the synovial fluid. The main reason was due to the noises between cartilage and meniscus were surfaced, then foster the daze of the synovial fluid outlines. As of that, it further undermining the detection validity of synovial fluid as its presence well dilated by the neighboring tissues (Fig. 8).

Different behavior attributed in the TSE sequence, the contrast it gathered especially on the cartilage-synovial turned the detection of contact length and the tibiofemoral contact area quantification far less complicated. Although the intensity differences were minimum, it reserved enough intensity to visualize all the essential tissues for the study needed (Fig. 6). This fact established on the MRI images attained from the TSE sequence, the synovial fluid presented in hyperintense was well distinguished between the cartilage and the meniscus. Meanwhile, the meniscus appeared in hypointense folds up its outlines perimeter and simultaneously increase the detection sensitivity level of the tissue. Despite the flexibility gained from the used of sense spine coil 15, the TSE sequence showed no attenuation in producing quality MRI images. This could not be attained by the SSFP and the FFE sequences, as both sequences resulted in indecisiveness of anterior meniscus intensity from a customized application of the sense spine coil 15. This can be discovered as the magnified signals from anterior knee were poorly received by the MRI (Fig. 8). As a result, the MRI conveniently rendered noises influenced of MRI images to the anterior meniscus, and decisively affected the measurement accuracy of the tibiofemoral contact area.

Figure 8. Red arrows pointing the anterior meniscus unveiled difference intensity deposited in the all three MRI sequences. As from poor signal received, noises uncovered anterior meniscus generated from SSFP and FFE sequences. White arrows pointing the synovial fluid locations, they were
undistinguishable in the SSFP and the FFE sequences, as low intensity difference enclosed between cartilage-synovial.

Furthermore, based on the TSE sequence alone, the tibiofemoral contact area in all positions showed a slightly higher result in the medial compartment. However, the contact area domination in medial compartment over lateral compartment was found not significant at P1 and P2 with $p > 0.05$. Interestingly, in the P3, the tibiofemoral contact area difference between the medial and the lateral compartments was found to be statistically significant with $p = 0.026$. From thoroughly analyzed the result, at least four subjects had a zero C-T-C contact area in the lateral compartment, while the rest of the subjects had a minimal of C-T-C contact area by average value of $50.06 \pm 50.06 \text{ mm}^2$. From percentage point of view, the result showed that the reduction of C-T-C contact area from the full extension position to the decubitus position were not exceeded 44.4% for the medial compartment and 49.2% for the lateral compartment. This percentage illustrated that C-T-C contact area is capable to enlarge both medial and lateral compartments as such C-T-M contact area expended. However, C-T-C contact area changed from position P2 and P3 were not statistically significant, with $p < 0.05$ (Fig. 7).

**Table 2.** The summary of cartilage-to-cartilage contact area (mm²) results for in-vivo study with subjects, $n \geq 10$

| Researchers         | MRI sequences                        | n  | Full Extension | Deep Flexion |
|---------------------|--------------------------------------|----|----------------|--------------|
|                     |                                      |    | Medial         | Lateral      | Medial       | Lateral      |
| Hinterwimmer et al. | T1- weighted Gradient Echo           | 12 | 438            | 185          | -            | -            |
| Patel et al.        | Spoiled Gradient Recalled Echo       | 14 | 374            | 276          | -            | -            |
| Yao et al.          | Gradient Recalled Echo               | 10 | 630            | 540          | 470          | 330          |
| Current study       | Turbo Spin Echo                      | 10 | 186            | 142          | 82           | 70           |

The limitations of this study rested on the limited numbers of MRI sequences for intensity analysis that were conducted. The reasoning was to stave off the possibility to the subjects suffered from claustrophobia and anxiety due to a longer imaging time. The limitations continued with the used of sense spine coil 15. Even though the used of sense spine coil 15 has greatly improved subjects’ flexibility, mobility and positions inside the confine MRI bore (Fig. 3). However, the coil had stricken vertically the MRI bore size, which originated from the increase of bed height for 10 cm. Thus, the coil limited the knee flexion angles to be tested (Fig. 9a). Also, this study unable to accurately quantify the existence of the contact between tibia and meniscus. This was due to misdetection or non-detection of the contact length occurred (Fig. 9b).
Figure 9. (a) Sense spine coil 15 stricken vertically the MRI bore size thus limiting the knee flexion angles, while (b) tibia to meniscus contact area data were not included, as it was over measured by the algorithm.

5. Conclusion
In conclusion, to accurately quantify the tibiofemoral contact area, the TSE sequence demonstrated diligently response through the MRI images by rendering lesser noises, shorter imaging time and more importantly produce high intensity differences of knee neighboring tissues. Subsequently, with those intense advantages, the TSE sequence showed that C-T-C and C-T-M contact areas have a significantly smaller compare to adrift results accumulated from the FFE and SSFP sequences. These results suggest that the TSE sequence yields an accurate contact length detection, a reproducible tibiofemoral contact area quantification and a proper blueprint of MRI sequence selection for future in vivo tibiofemoral contact area study.

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