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Magnetic Resonance Imaging Sequence Analysis of Tibiofemoral Contact Area Assisted by MATLAB Software

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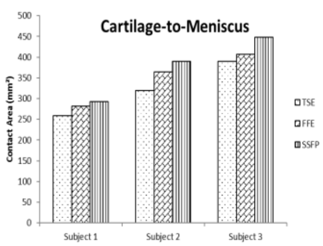
Graphical abstract



Abstract

The objective of this study is to find the suitable MRI sequence for a tibiofemoral contact area study assisted by MATLAB software. An MRI image's color contrast quality and optimal scanning time are the optimized parameters. The hypothesis of this study is that the protocol sequence bonding with the fastest scanning time should have greatest efficiency error. Three healthy subjects' knees were scanned in the prone position under Turbo Spin Echo (TSE), Fast Field Echo (FFE) and Steady State Free Precision (SSFP) sequences. A total 34 slices was acquired for each sequence, each slices being 2-mm thick and a 0.2-mm gap between slices. The results of the analysis revealed that the FFE and the SSFP sequences resulted in additional *8.17%* and *14.26%* efficiency error of contact area between the femoral cartilage and the meniscus, respectively. Those errors were even greater in the contact area between the femoral and the tibial cartilages, where the FFE sequence estimated the error at about *19.82%*, whereas for the SSFP sequence, the extra contact area measured about *22.89%*. All calculation percentages were relative to the TSE sequence. It is suggested that the TSE sequence is a suitable MRI sequence for this study, due to its excellent image color contrast intensity and clocked optimal scanning time.

Keywords: Magnetic resonance imaging, sequence analysis, tibiofemoral contact area, knee, meniscus, knee arthroplasty

1.0 INTRODUCTION

Prevalence studies show that a total knee arthroplasty (TKA) implant could last for at least 7 to 9 years [1-3]. With the recently introduced high-flex TKA design, however, several cases of early aseptic loosening have been reported [4, 5]. Some of the works reviewed for this study indicate that some researchers agree that design of the high-flex TKA implant linked to the loosening caused [4-7] and some do not [8, 9]. This debate has led to a number of comparison studies featuring both sides [10].

Anatomically, the human knee has a more efficient geometry when it comes to distributing bodyweight as compared to the knee arthroplasty implant. During activities that involve a high degree of knee flexion, the contact area of cartilage-to-cartilage decreases about 25% for normal knee as suggested by [11]. This percentages, however, excluded the contact area covered by the menisci in normal knees. Others studies have suggested that the meniscus dynamically increased its contact area during knee flexion [11-14]. The prosthesis sides clear indicate that the present contact areas in TKA implants are the substitute contact areas between femoral and tibial cartilages, and no the meniscus contact areas involve. Thus, the absence of the meniscus after a primary TKA would indeed result in high local pressure on the tibial insert. For that reason, a further understanding of tibiofemoral contact areas in a healthy knee could lead to new and improved features for TKA implants.

It is widely known that neither x-ray nor computed tomography (CT) scanners are able to visualize internal soft tissues. The fact is, this study requires the visual images of synovial fluids, menisci and cartilage, all of which are soft tissues. Hence, to accomplish this purpose, those tissues could be digitally visualized using magnetic resonance imaging (MRI), where images clarity depends on the scanner used and the sequence applied. However, this method is costly, and each MRI scanner has number of built-in MRI sequences for various specific studies. To date, only a few researchers have done studies on the analysis of tibiofemoral contact areas [15, 16], and none has managed to optimize the suitable MRI sequence for this study.

Therefore, the objective of this project is to analyze the suitable MRI protocol sequence for a contact area study by using MATLAB software (Math-Works, Inc., Natick, MA). The optimized parameters in this analysis were based on the clearest observation of related soft tissues in MRI images within optimal scanning time periods. The preliminary hypothesis of this study is that the protocol sequence associated with a fastest scanning time results in a *greatest efficiency* error.

2.0 METHODS

Three best sequences which produced the clearest visible image of cartilages and the meniscus were selected. They are the Turbo Spin Echo (TSE), the Fast Field Echo (FFE) and the Steady State Free Precession (SSFP). The sequences were based on observations were made based on previous studies and literature study [17, 18]. An Achieva 3.0T TX MRI scanner and a coil type SENSE spine coil 15 were used in this study. Both are produced by Philips Healthcare, Andover, MA.

All of the selected sequences above were tested on three healthy subjects' knees. They all consented to the experimental procedure which was approved by the USM Human Research Ethics Committee. Normal safety procedures for MRI screening were applied in this study. Any items of clothing with metallic threads or fasteners were avoided. The pants restricting the knee's ability to move naturally were also avoided. All subjects were instructed to extend their knees in the prone position and the coil was placed as shown in *Figure1*. The reason subjects were positioned prone and the SENSE spine coil 15 was used, was for our future research objective, which is to measure tibiofemoral contact area in a flexed knee.

Figure 1 Subject three was positioned prone with both knees in fully extended. The coil was placed on the MRI bed and leg supports were used to prevent movement which could cause motion distortion.

A total of 34 slices for each sequence was set to generate a consistent slice thickness at 2mm and the gap between the slices was 0.2mm for each of the three subjects' screening. The field of view was set at 150 × 150mm, with a 512 × 512 matrix resulting in an in-plane resolution at 96ppi or 0.27mm per pixel. None of the MRI images were reconstructed images. The detailed images acquisition for all sequences were summarized in *Table 1*.

To analyze the tibiofemoral contact area using the MRI images, a customized coding script was used to assist MATLAB software step-by-step from the identification to contact area calculation. The first line of the coding script was to read the MRI image in the digital RGB format. The MRI images then were cropped at the distal femur area of interest, to reduce the tracing processing time of the contact length. The cropped images then were inverted into the binary system format, the black pixels were numbered as 0 while white pixels were numbered as 1. At this level, the images were presented solely as numbers in the matrix. Next, the numbers in the matrix were expended vertically and horizontally by 1-3 pixels in order to remove the artifacts on the images. The dilate function was used to smoothen the images by the additional 1-3 adjacent pixels to nonnegative scalars in the diamond shape direction. The matrix were then re-inverted back to allow the boundary trace routine to track the contact length. However, initial coordinates had to be manually fed so that the boundary trace routine could begin. Once the contact lengths on the MRI images are tracked, the red pixels and the green pixels will be marked on the original MRI images.

Table 1 MRI sequences parameter

Sequence	Dimensional space	TR (ms)	TE (ms)	Flip Angle (deg)	Bandwidth (Hz)	Scanned Time (s)
TSE	2D	4814	30	90	291.7	332.1
FFE	2D	500	5.8	50	216.3	342.5
SSFP	2D	623	12	20	216.8	403.5

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

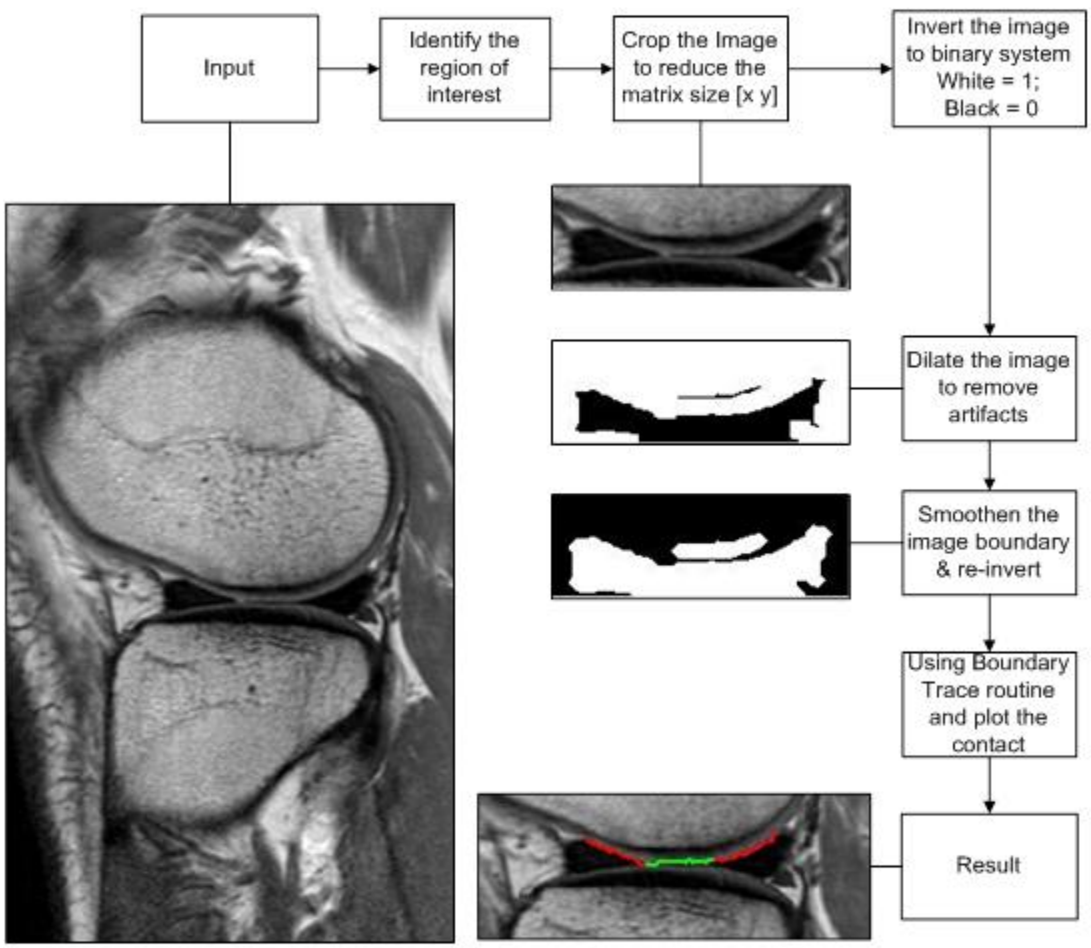


Figure 2 A MATLAB's script process flow; red pixels represent as contact length between femoral cartilage and meniscus, while green pixels are the contact length between femoral and tibial cartilages

The final step of the coding script was to calculate the number of pixels representing the marked contact length in the MRI images. The detailed process flow of the customized coding script is shown in the Figure 2. The cartilage-to-meniscus and cartilage-to-cartilage contact areas were calculated by totaling up all the contact regions. The contact region is the contact area of an MRI image slice, which is calculated by multiplying contact length and the slice thickness. Eq. 1 is the combination of all the mathematical equations used to calculate the contact area.

$$Contact\ area = \sum contact\ region\ (contact\ length \times slice\ thickness) \qquad (1)$$

3.0 RESULTS AND DISCUSSION

From the results shown in Figure 4 and 5, the TSE sequence composed a smaller contact area compared to other sequences. The average cartilage-to-meniscus contact area for the TSE sequence was about 322.56 ± 65.45mm2. For the FFE and the SSFP sequences, on the other hand, the resulting values were 350.66 ± 63.52mm2 and 376.94 ± 78.60mm2, respectively. Furthermore, comparison analysis showed an excess of 8.17% for the cartilage-to-meniscus contact area for the FFE sequence, and 14.26% of extra contact areas for the SSFP sequence. On the other hand, the average cartilage-to-cartilage contact area for the TSE sequence was about 208.67 ± 30.26mm2. Meanwhile, for the FFE and the SSFP sequences, the values were 258.76 ± 15.62mm2 and 270.05 ± 9.70mm2, respectively. The comparison analysis of cartilage-to-cartilage contact areas shows 19.62% of extra contact areas for the TSE sequence and 22.89% of extra contact areas for the SSFP sequence. It should be noted that, all the comparison analysis percentages were calculated relative to the TSE sequence. It has been accepted from the established results that the TSE sequence resulted in the smallest contact areas compared to others. This result indicates the TSE sequence results in an accurate contact area calculation and the quality of the MRI images produced were the best in terms of color contrast intensity. This can be confirmed by comparing images between sequences, which show that the other two sequences, namely the SSFP and the FFE sequences resulted in inconsistent color contrast of soft tissues. Some of the soft tissues have missed on the MRI images and some images were unable to distinguish between adjacent soft tissues.

Figure 3 Comparison sequences for subject one: The TSE sequence has better color contrast intensity between the synovial fluid, the meniscus and the cartilage, compared to other sequences

Figure3 compares the three sequences at the same slice number for subject one. The FFE and the SSFP sequences images were unable to visualize the presence of the synovial fluid as indicated by white arrows. Moreover, the FFE sequence, also known by a general acronym (GRE) Gradient Recalled Echo resulted in an image that was hyperintense at the anterior horn meniscus and hypointense at the posterior horn meniscus. This inconsistency on the FFE slice may become worse at a thinner MRI image thickness. The absence of the anterior meniscus on the FFE sequence MRI image resulted in inaccurate contact area analysis, as established above.

For the SSFP sequence, on the other hand, the cartilage on the femoral and tibial bones shows a great contrast between the trabecular and cartilage. However, this sequence resulted in an isointense (same intensity) image color between the menisci and the synovial fluids, which resulted in MATLAB software mistakenly analyzing the in-plane image of the contact length. As a result, the SSFP sequence produced a greater contact area than the other sequences. This consequence indicates that insufficient contrast in the color intensity for the SSFP sequence's images result in incorrect analysis by overestimating the contact regions.

In this test, the analysis results were the opposite of what our early hypothesis predicted. Our preliminary hypothesis says that the shortest scanning time will result in the greatest efficiency errors in contact areas. Evidently, the actual results were the other way around. The TSE sequence produced excellent image contrast compared to other sequences. Although this TSE sequence generated 25.8% more bandwidth than the other sequences, the signal is still categorized as super low frequency (SLF). According to [19], the exposed frequency at SLF level, given this bandwidth, extremely unlike to have side effects on the human body. To summarize this study, the TSE sequence is suggested as the best sequence of choice for tibiofemoral contact area analysis. This suggestion is based on its excellent image contrast and the fact that it had the shortest scanning time.

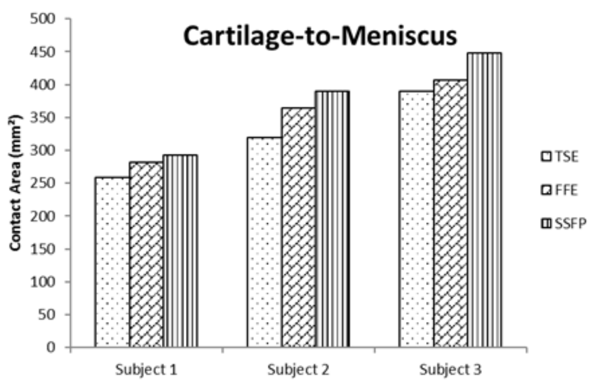


Figure 4 Tibiofemoral contact area between cartilage and meniscus for different type of MRI sequences

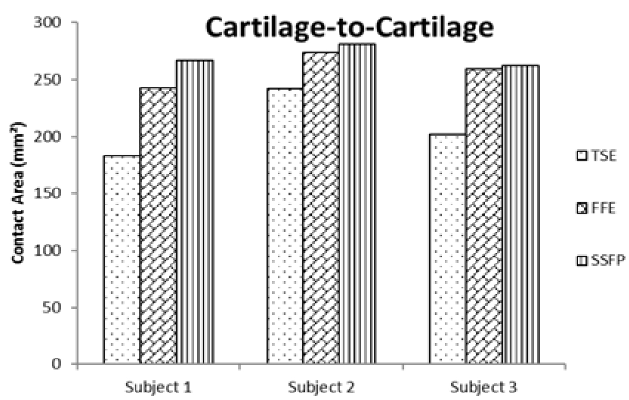


Figure 5 Contact area between femoral and tibial cartilage for different MRI sequence

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