ORIGINAL CONTRIBUTION

Multiple Half-second Acquisition Method of the Moving Knee Joint : Kinematic MR Imaging of the Anterior Cruciate Ligament

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Objective : The objective of this study was to delineate the moving anterior cruciate ligament (ACL) with multiple rapid magnetic resonance (MR) imaging.

Methods and Subjects : Rapid gradient echo MR images with an one-shot acquisition time of a half-second were accomplished by short repetition time and phase encoding reduction. Using a mobile knee brace and a flexible surface coil, half-second acquisitions were sequentially acquired during active, constant knee movement. Sixteen knees with intact ACLs and 27 knees with arthroscopically proven ACL tears were examined.

Results and conclusions : Normal ACLs were identified as moving linear low-intensities. The ligaments were readily identified as straight or minimally curved structures when the knee was in semi-flexion compared to the knee extension. Torn ACLs were demonstrated as moving fragments or an amorphous configuration. Intermittent appearances of joint fluid interrupted the ligamentous continuities. Compared to the static images, no significant superiority of the kinematic imaging was found in diagnosis of ACL tears. However, this instant kinematic imaging is feasible with a standard MR system and can provide morphological information for functional analysis of the knee.

INTRODUCTION

Functional magnetic resonance (MR) studies evaluating joint motion revealed temporal alterations of physiologic and pathologic morphology in the mobile joints. The term "kinematic" was introduced by Shellock et al.[1)] and sequentially acquired MR imaging of the patellofemoral joint motion is clinically useful[2)]. Kinematic studies have been reported in other joints, including the temporomandibular joint[3)], the wrist[4)], and the shoulder[5)]. These initial reports of kinematic studies were

Keywords knee, anterior cruciate ligament, rapid imaging, cine MRI, kinematic examination

based on static images ; multiple sequential images in various degrees of joint position were displayed in a cine loop.

A cine MR imaging system that can obtain kinematic images of the knee joint during actual knee movement was introduced[6]. The cine technique is clinically useful in assessing the continuity of crucial ligaments[7]. However, this technique required a dedicated drive system and was complicated to operate, it could not be generalized in routine examinations. If ultra-fast acquisition that freezes knee motion and acquires sequential images during one or a few motion cycles is achieved in clinical machines, the kinematic imaging can be performed without difficulties. A few trials have been reported using ultra-fast gradient echo sequence for the slowly moving patellofemoral joint[8].

Delineation of the cruciate ligament, especially the anterior cruciate ligament (ACL), is essential for the diagnosis of internal derangement of the knee, because tears of the ACL are the most common component of knee injuries[9]. However, the ACL is slightly thinner and has a more oblique course, visualization of the entire ACL by kinematic imaging is more difficult than that of posterior cruciate ligament (PCL). To our knowledge, there are no previous kinematic studies attempting to demonstrate the moving cruciate ligaments. This study is an initial trial to obtain kinematic MR imaging of the moving knee joint, focusing on delineation of the ACL using multiple sequential images.

SUBJECTS AND METHODS

Subjects—

The technique was used in 43 knees. In 33 patients, 18 men and 15 women ranging in age from 16 to 43 years, who had knee injuries, 34 knee joints were examined using MR imaging and subsequent arthroscopic examination. All the arthroscopic examinations were performed within the six-week period following the MR examinations. Using arthroscopy, we found 27 torn and 7 intact ACLs. In 8 healthy subjects (6 men and 2 women ranging in age from 22 to 31 years) who had no history of knee pain or injury, 9 knee joints were also examined using MR imaging. Thus, a total of 16 knees with intact ACLs and 27 knees with torn ACLs were studied.

Knee brace—

A non-ferromagnetic mobile knee brace was made to fix the thigh and enable the knee joint to bent freely inside the magnet bore of the MR unit (Fig. 1). Within the confined space of the magnet bore, the knee joint could reach full-extension and bend vertically to a semi-flexed position. Depending on the length of the subject's lower leg, maximal flexion ranged from 40° to 55°, averaging 45°.

Active knee motion—

Subjects in a supine position placed the knee in the mobile brace with the foot fixed by Velcro straps to minimize the sideway displacement (Fig. 1). Prior to the scanning, the subjects practiced moving the knee with a slow and consistent rate of approximately 10 seconds for one extension-flexion cycle. Inside the magnet bore, a periodic signal played once

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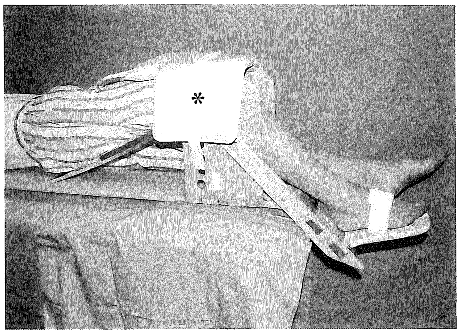


Fig. 1. A mobile knee brace and a flexible surface coil (asterisk). The knee can bend vertically to a semi-flexed position (averaging 45° of flexion) and reach full-extension within the confines of the superconducting magnet bore. The subject intentionally swings her lower leg at a constant rate of 10 seconds for one extension-flexion cycle. A flexible surface coil, covering the anterior and both lateral aspects of the knee, enabling the knee to extend and flex freely, produced relatively high-quality kinematic images.

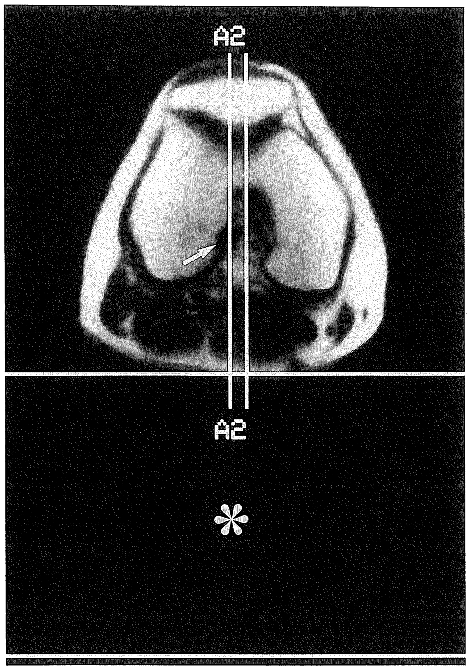
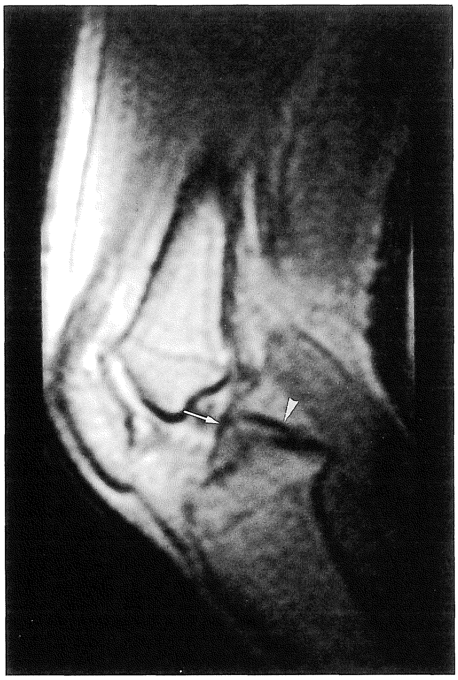


Fig. 2. Section prescription on the localizing image. On axial image with the knee in semi-flexion, two contiguous 5-mm-thick sagittal sections were determined in the lateral aspect of the intercondylar notch. The lateral section ("A2") was set to cross the point of tibial insertion of the ACL (arrow). Regional presaturation (asterisk) was applied posterior to the knee joint to suppress backfolding from the flexing lower leg.

every second by the MRI music systems through stethoscope style headsets (Genesis System, Magnacoustics, Atlantic Beach, New York) to guide the subject in maintaining a consistent rate of knee motion. With a sign from the operator, the subject began active knee motion and continued for two reciprocating extension-flexion cycles over approximately 20 seconds, during which time the sequential scanning for 15 seconds was completed. No subject in this study complained of any discomfort.

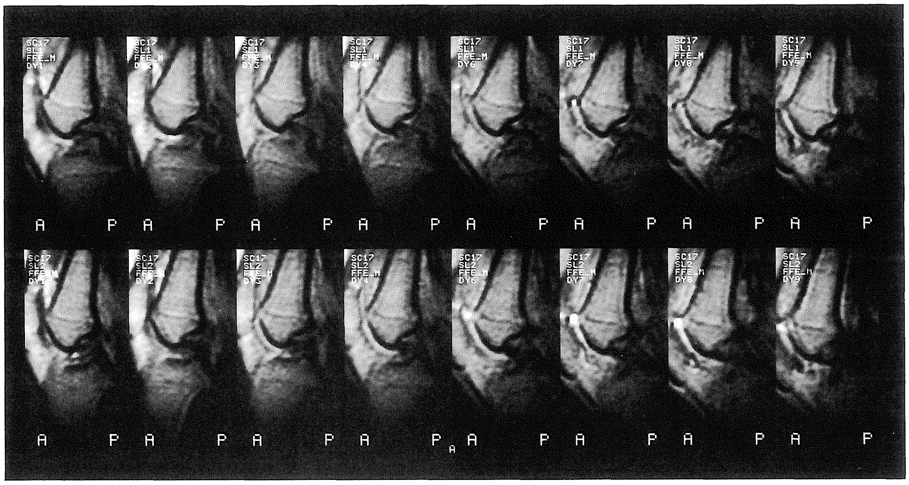
Kinematic MR imaging—

The MR examinations were performed using a 1.5 T MR unit (Gyroscan ACS-II, Philips Medical Systems, Best, The Netherlands). A commercially available, flexible surface coil (E1 coil, Philips Medical Systems, Best, Netherlands) composed of two loops was wrapped around the knee, allowing the knee to bend freely (Fig. 1). A fast gradient echo pulse sequence was employed and the following parameters were optimized to delineate the moving ACL by the initial volunteer trials : repetition time (TR), 7.3–10.0 ms ; echo time (TE), 3.1–3.7 ms ; flip angle, 30 degree ; matrix and field of view (FOV), 128 × 102 and 250 × 125 mm rectangular FOV (20% phase encoding reduction combined with 50% FOV reduction resulting in 51 phase encoding steps) ; section thickness, 5 mm ; and number of signal averages, one. The acquisition time ranged from 0.37 to 0.51 second per single image. On localizing axial images with the knee in flexion,



a

Fig. 3. Normal knee. (a) One frame from sequentially acquired half-second MR images of moving knee with intact ACL (arrow) and PCL (arrowhead). The ACL appears as straight low-intensity and the PCL appears as a thicker cord with lower signal intensity than that of the ACL. (b) Sets of sequential images of the two contiguous sections. Eight frames from the medial section in upper row and eight frames from the lateral section (section "A2" in Fig. 2) in lower row. The ACL is more readily identified as a low-intensity cord when the knee is in semi-flexion than in extension. The PCL appears stretched during knee flexion and bent during extension.



b

two contiguous 5-mm-thick sagittal sections were determined in the lateral aspect of the intercondylar notch (Fig. 2). Regional presaturation was applied just posterior to the knee to suppress backfolding from the flexing lower leg (Fig. 2). A series of half-second scans were obtained from the two sections alternately so that each section was imaged once per second. The total scan time was typically 15 seconds for 30 shots of the two sections (15 of each), which was sufficient to include at least one extension-flexion cycle of 10 seconds in the continuously moving knee joint. The images were loaded into the attached imaging workstation

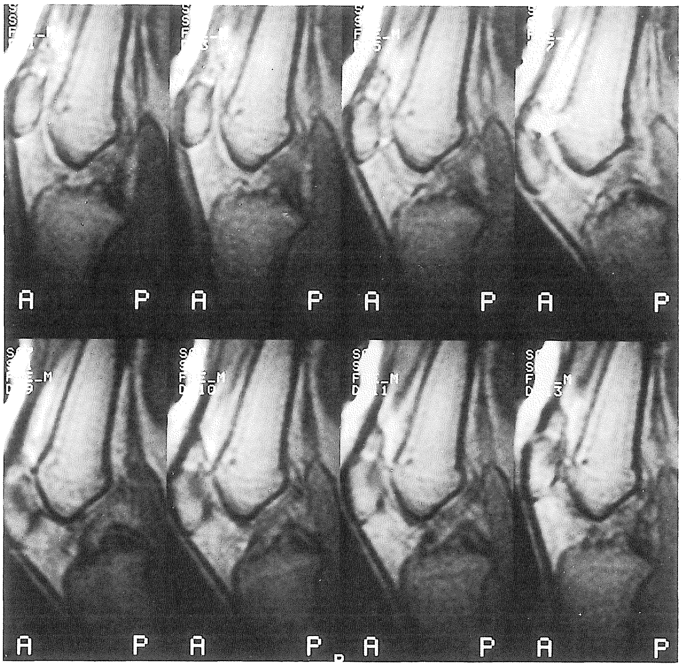


Fig. 4. Acute ACL tear. Eight frames from a set of one-shot images of the knee from full extension (upper-left image) to 40° of flexion (lower-left image) and back to extension (lower-right image). When the knee is semi-flexed, ACL is identified as a curved and thick configuration with faint intermediate intensity. The absence of a solid structure connecting the femoral and tibial attachments suggested ligamentous discontinuity without remaining functioning bundles.

(Gyroview, Philips Medical Systems, Best, The Netherlands) and displayed in a kinematic manner.

Static MR imaging—

Using the identical knee brace and flexible surface coil, sets of 3-mm-thick (with 0.3-mm gaps) oblique sagittal sections were determined with the knee in nearly fully-extended position. Proton-weighted, turbo spin echo MR images were obtained with a TR of 1300 ms, an TE of 12 ms, a turbo factor (echo train length) of 6, a 16-cm rectangular FOV, a 201×256 acquisition matrix, and four averagings. The acquisition time was approximately 4 minutes.

Image analysis—

Two imaging modalities of kinematic imaging and static images were evaluated by two of the authors with all final interpretations representing a consensus. The reviewers diagnosed the MR imaging of all the cases without knowledge of clinical test or arthroscopic examination results. The kinematic imaging and static images of the same subject were interpreted independently in separate sessions. Using the arthroscopic results as gold standards, the differences in sensitivity and specificity for detection of ACL tears were evaluated by using the McNemar exact test with the statistical significance at the level of $P<0.05$.

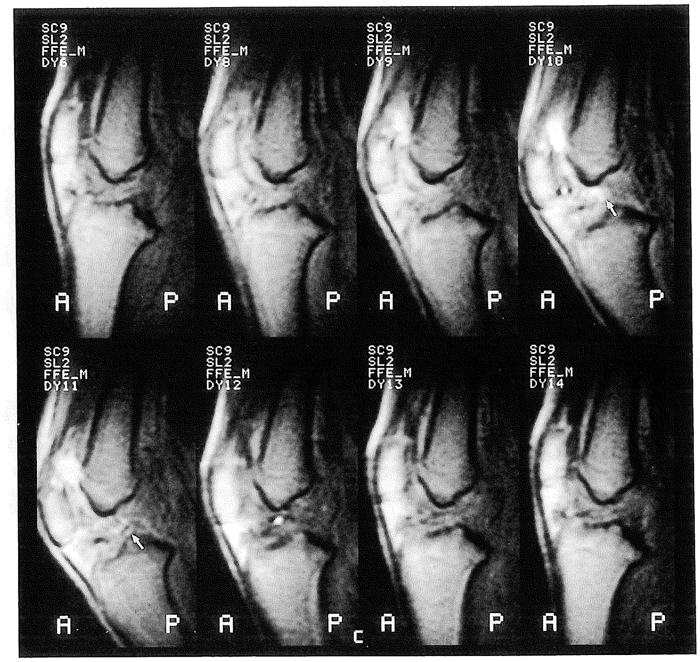


Fig. 5. Chronic ACL tear. Eight frames from a set of one-shot images of the knee from full extension (upper-left image) to 40° of flexion (lower-left image) and back to extension. On all frames, ligamentous continuity can not be identified. Joint fluid appearing at the site of the ACL (arrows) indicated disruption of the ligament.

Table Diagnostic Results Using Kinematic and Static MR Imaging of ACL Tears

MR Imaging	Normal ACL (n=16)		Torn ACL (n=27)		Sensitivity (%)	Specificity (%)
	True-Negative	False-Positive	True-Positive	False-Negative		
Kinematic Imaging	14	2*	26	1	96.3	87.5
Static Images	14	2**	25	2	92.9	87.5

* : Two false positive cases by the kinematic imaging were due to degraded imaging quality.

** : Two false positive cases by the static images were correctly diagnosed using kinematic MR imaging.

RESULTS

The sequentially acquired half-second MR images were able to delineate the cruciate ligaments, which were identified as moving linear low-intensities. Compared to the ACL, the PCL appeared as a thicker cord with a lower signal intensity (Fig. 3(a)). The shape of the cruciate ligaments changed during knee motion (Fig. 3(b)). Normal ACLs were readily identified as straight or minimally curved low-intensity structures when the knee was in the semi-flexed phase compared to that when the knee extended. The PCL appeared stretched during

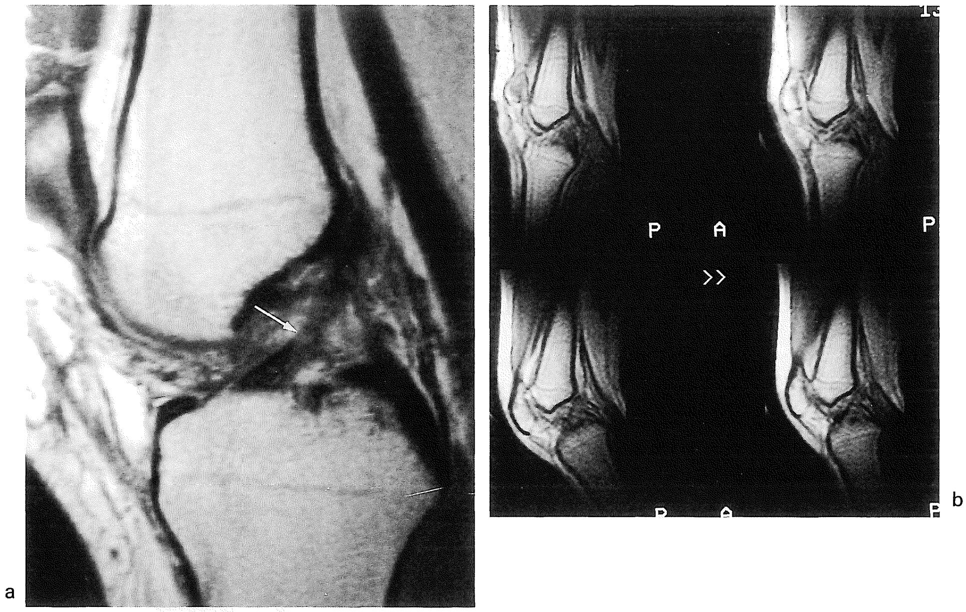


Fig. 6. Intact ACL (a) In static image, a faint high-intensity area at the anterior border of mid ACL (arrow) was diagnosed as a tear. (b) Four frames from a set of one-shot images of the same knee from full extension (upper-left image) to 40° of flexion (lower-left image). The kinematic images demonstrated a solid low-intensity cord, which was correctly diagnosed as an intact ligament.

knee flexion and bent during extension phase.

Torn ACLs were demonstrated as moving fragments or showed an empty intercondylar space. With an acute tear, the ligament was identified as a curved and thick configuration with faint, intermediate intensity (Fig. 4). No solid structure connecting the femoral and tibial attachments was identified in any of the sequential images for either of the two sections, which suggested ligamentous discontinuity without any functioning bundles. Chronically torn ACL was indicated as an amorphous structure replacing ligamentous bundles and interrupting the continuity (Fig. 5). Joint fluid which appeared at the site of the ACL and interrupted the ligamentous continuity, confirmed the diagnosis of the ligament disruption.

The diagnostic results of ACL tears for kinematic and static MR imaging are summarized in the Table. We found that 26 of the 27 arthroscopically proven ACL tears and 14 of 16 normal ACLs were correctly identified using kinematic MR imaging, giving a sensitivity of 96% and a specificity of 88%. The static MR imaging had a sensitivity of 93% and a specificity of 88%. Two cases of normal ACLs misdiagnosed as having tears by the static MR images (Fig. 6(a)) were correctly diagnosed using kinematic MR imaging (Fig. 6(b)). Two false positive cases by the kinematic imaging were due to degraded imaging quality from sideway displacement of the moving knees. One ACL tear case was diagnosed as false negative both on kinematic and static imaging. There were no statistically significant differences in sensitivity and specificity for detecting ACL tears.

DISCUSSION

Half-second images of an adequate imaging quality for delineating moving ACLs were obtained using a flexible surface coil and a mobile knee brace in a standard superconducting MR unit. Recent progress in MR technology increased the space available with open magnets[10] and there are some dedicated units for the extremities which are advantageous in performing kinematic examinations of knee movement. Using a standard MR system, visualization of the normal and torn ACLs with high speed imaging indicated that kinematic MR imaging of the moving knee is feasible and advantageous in evaluating the continuity and tension in the cruciate ligaments. More rapid imaging sequences, including echo planar imaging ; EPI[11] and gradient- and spin-echo ; GRASE[12], are now extending the commercial availability, and will facilitate the kinematic studies with clinical utilities. Combining rapid image reconstruction with faster acquisition, MR fluoroscopic technique will become a useful method of delineating moving organs[13),14]. In addition to static MR imaging, functional analysis by kinematic imaging of the moving knee joint will become a widely accepted and useful clinical examination.

Using a fast gradient echo sequence combining reduced encoding steps with rectangular FOV, a half-second acquisition time per one-shot frame was accomplished with a standard MR system. To obtain high quality kinematic images by fast scan MR technique, it is crucial that the acquisition time is short enough to freeze motion. However, counterbalancing acquisition time vs. spatial resolution, and also acquisition time vs. signal-to-noise ratio (SNR) is a great challenge. Decreased acquisition time sacrifices both spatial resolution and SNR. The spatial resolution of approximately 2 mm (1 mm for the viewing matrix) was the maximal limit for delineating the ACL. Under this matrix resolution and section thickness, the shortest achievable TR of 7.3 ms enabled a scan time as short as 0.37 second. The knee motion rate of 10 seconds for a single extension-flexion cycle might be slower than physiological knee motion, however, this is a compromise for the acquisition time of half-second.

Using a flexible coil that covers the entire knee facilitated a gain in SNR and obtained relatively high-quality kinematic images of the moving knee. To pursue constant knee motion with restricted sideway displacement, using knee brace is also essential. With the combined use of the flexible surface coil and the mobile knee brace, the knee could swing vertically up to full-extension and down to semi-flexion supported by the brace, and was sequentially imaged to delineate the cruciate ligaments during active motion.

The contiguous sagittal sections were determined on the basis of the axial localizing images to obtain the whole length of the ACL. A single 5-mm-thick section might not display the entire length of the ACL with oblique trajectory in the intercondylar notch. Two contiguous 5-mm sections were imaged alternately, allowing the entire ACL to be shown on a dual-view display as indicated in Fig. 3(b).

Kinematic images with the knee in semi-flexion delineated ACLs more readily than those with the knee extended. In static fast spin echo MR images, the ACLs were more readily identified as low-intensity cords when the knees were in semi-flexion than in extension[15]. In a static sagittal image with the knee in extension, the ACL showed a greater signal intensity than the PCL. This was reported due to obliquely oriented ligamentous fibers[16] or so-called ''magic angle'' effect[17]. Moreover, even if the knee were to swing vertically with restricted sideway motion using the knee brace, physiologic external rotation of the tibia at the full-extension might lead to rotational displacement from the sagittal sections.

In contrast to the passive motion in the previously reported cine imaging, the knee motion in this study was driven by active force which suggests a more physiological simulation of the knee motion. The clinical usefulness of active motion has been reported in kinematic studies of the patellofemoral joint[18]. Compared to the previously reported cine imaging system of the knee which has demonstrated diagnostic value in assessing ligamentous continuity[7], substantial reduction in the total scan time of 15 second and the fact that dedicated driving and gating systems are not required, suggest that the sequential rapid imaging of the moving knee joint is practical and can be included along with routine MRI examination of the knee. In our clinical site, all the knee examinations, including surveys for suspected meniscal pathologies, were performed by using the flexible coil combined with the knee brace. In addition to the series of static imaging with the knee in semiflexion or extension, kinematic scans can be performed anytime without the need for patient re-positioning.

In conclusion, kinematic MR imaging delineated moving cruciate ligaments during active knee motion and could be obtained with a standard MR system. Diagnostic superiority over the static images could not be found in this study, however, kinematic imaging of the moving knee joint and functional analysis of the knee motion will be practicable in addition to static MR imaging. The increased information obtained with kinematic imaging may warrant continued investigation and clinical application.

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