

1 **Experimental pilot study for augmented reality-enhanced elbow arthroscopy**

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16 **Running title;** Augmented reality-enhanced elbow arthroscopy

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18

19 **Abstract**

20 **Background:** The purpose of this study was to develop and evaluate a novel elbow
21 arthroscopy system with superimposed bone and nerve visualization based on
22 preoperative computed tomography (CT) and magnetic resonance imaging (MRI) data.

23 **Methods:** We obtained bone and nerve segmentation data by CT and MRI, respectively,
24 of the elbow of a healthy human volunteer and cadaveric Japanese monkey. A life size 3-
25 dimensional (3D) model of human organs and frame was constructed using a stereo-
26 lithographic 3D printer. Elbow arthroscopy was performed using the elbow of a cadaveric
27 Japanese monkey. The augmented reality (AR) range of error was examined at 1 cm and
28 2 cm scope–object distances.

29 **Results:** We successfully performed AR arthroscopy using the life-size 3D elbow model
30 and the elbow of the cadaveric Japanese monkey by making anteromedial and posterior
31 portals. The computer graphics (CG) position and shape were initially different because
32 of lens distortion. The CG position and shape were corrected to match the arthroscopic
33 view using lens distortion parameter estimates based on the calibration pattern. AR
34 position and shape errors were 2.3 mm at 1 cm scope–object distance and 3.6 mm at 2 cm
35 scope–object distance.

36 **Conclusion:** We attained reasonable accuracy and demonstrated the working of the

37 designed system. Given the multiple applications of AR-enhanced arthroscopic
38 visualization, it has the potential to be the next-generation technology for arthroscopy.
39 This technique will contribute the reduction of serious complications associated with
40 elbow arthroscopy.

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42 **Keywords** augmented reality, elbow, arthroscopy

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55 **Background**

56 Available evidence supports use of elbow arthroscopy to manage multiple
57 conditions including rheumatoid arthritis, osteoarthritis, tennis elbow, and osteochondritis
58 dissecans. A major drawback of elbow arthroscopy is the risk of intraoperative
59 complications, including serious neurovascular injuries¹. The small working space and
60 near adjacency of neurovascular and arthroscopic portals make elbow arthroscopy a
61 technically demanding procedure. Successful elbow arthroscopy requires extensive
62 knowledge of the spatial correlations among the neurovasculature, entry portals and joint
63 structures.

64 Recent advancements in sophisticated image processing technology have made
65 precise preoperative simulations a possibility, and they are becoming increasingly
66 common in clinical practice². But this valuable set of information is ineffectively utilized
67 in elbow arthroscopy at arguably the most decisive point: during the procedure³. The
68 ability to access such data that is optimized for use and seamlessly integrated into the
69 surgical navigation system has remained elusive. We propose that the safety of standard
70 elbow arthroscopy can be improved by incorporating augmented reality (AR). AR can
71 allow delivery of selective complex and highly useful information through computer
72 graphics (CG) superimposed onto real-time video.

73 The purpose of this study is to develop and evaluate a novel elbow arthroscopy
74 system with superimposed bone and nerve visualizations based on computed tomography
75 (CT) and magnetic resonance imaging (MRI) data. We hypothesize that the accuracy of
76 the resulting AR enhancement to standard arthroscopy would be acceptable.

77

78 **Methods**

79 This study was conducted under the approval of local institutional review board.

80 **Experiment 1.**

81 Data collection, processing and 3-dimensional (3D) modeling of body organs

82 Skin, bone, and nerve segmentation data of the elbow of a healthy human
83 volunteer were obtained by CT and MRI, respectively. Inter-modal voxel registration was
84 performed using ANT software with a SyN non-linear registration algorithm and affin
85 registration⁴. Segmentation and refinement were performed using VoTracer software
86 (Riken, Wako, Japan, <http://www.riken.jp/briect/Ijiri/VoTracer/>)⁵. All segmented lesion
87 data were exported as Standard Triangulated Language (STL) data.

88 We added support frame STL data to correctly coordinate bones and nerves upon
89 3D printing and printed a life size 3D model of organs and frame using a stereo-
90 lithographic 3D printer (Object500 Connex, Stratasys Ltd, US.). (Fig. 1)

91

92 Setup of elbow arthroscopy and device tracking system.

93 We used a tracking system (MicronTracker3; ClaroNav, Toronto, Canada) for
94 surgical device tracking. MicronTracker3 is an optical pose tracking system with a unique
95 ability to track an unlimited number of tools simultaneously.

96 Each tracking marker used in the system was composed of black and white regions
97 and system computed target locations at the intersection of four high-contrast regions.
98 Each of the four black and white boundary lines independently served to pinpoint the
99 location of targets called 'Xpoints'.

100 Unlike bright spot markers, Xpoints have information on location and orientation.
101 This additional discriminating characteristic greatly reduces erroneous mismatches
102 between targets on left and right images. It also reduces marker misidentification, as
103 matching the characteristics of the observed targets against templates leads to
104 identification. As misleading bright reflection spots are more common in an operating
105 environment compared with Xpoints, the use of Xpoints greatly reduces the risk of
106 misidentification.

107 The markers were identified with reference to a marker template database, and
108 allowed distinguishing between multiple different instruments. Furthermore, the database

109 can be updated during run-time, allowing new marker templates to be added simply by
110 presenting them to the camera and assigning a name to them. We placed different markers
111 onto each 3D model baseplate and used the arthroscopy camera for tracking. To stabilize
112 markers on the arthroscopy camera, we made custom stainless-steel guides that could
113 attach markers on the arthroscope. (Fig. 2a)

114

115 Augmented reality image processing during training surgery

116 While performing elbow arthroscopy on the generated 3D model, an AR
117 calculated CG image was superimposed onto the arthroscopic video view by our AR
118 system.

119 The system summary is as follows (Fig. 2b).

120

121 1. Arthroscopy image data were captured on the computer through a digital video
122 capture card connected to the arthroscopy camera system.

123 2. The data of the 3D model base plate and the arthroscopy camera body loci were
124 provided by MicronTracker3, which was able to trace target information using a
125 customized software developed using the MicronTracker software developers' kit.

126 Coordination system of the 3D model of organs and the arthroscopy camera were

127 defined as Σ_{\square} and Σ_{\square} . Transformation matrix from MicronTracker3 sensor (\square_{\square}) to the
128 marker reference point (fiducial point) of Σ_{\square} : ($\square_{\square 0} = \Sigma_{\square(x,y,z=0,0,0)}$) and Σ_A : ($\square_{\square 0} =$
129 $\Sigma_{\square(x,y,z=0,0,0)}$) was found by stereo-triangulating the optical marker defined as \square_{\square}
130 and \square_{\square} . Transformation matrix from $\square_{\square 0}$ to each organ STL model reference point
131 \square_{\square} was pre-defined as \square_{\square} (Though organ models include skin, radius, ulna, humerus,
132 radial nerve, ulnar nerve, median nerve, musculocutaneous nerve, and they were
133 handled separately in calculation, 3D relationship between these models are static,
134 therefore the reference point of these models were expressed as single point in this
135 expression (\square_{\square})), and $\square_{\square 0}$ to the tip of arthroscopy light rod \square_{\square} was pre-defined as
136 \square_{\square} before examination.

137 3. Our custom-made software installed on the computer calculated each 3D organ model
138 and arthroscopy light fiber rod position and direction. Position of virtual camera was
139 placed on \square_{\square} and rotated according to the lens-offset angle (In this experiment, it was
140 30 degrees.); therefore the coordination system of camera sight Σ_{\square} must consider this
141 angle.

142 Calculation to transform Σ_{\square} to Σ_{\square} is as follows;

144
$$\Sigma_{\square} = \square_{\square} \Sigma_A = \frac{\square_{\square}}{\square_{\square}} \Sigma_{\square}$$

143 Each 3D organ model data was rendered according to this transformation. A

145 homogenous transformation can be constructed to register the virtual arthroscopy
146 view to the real arthroscopy view. This calculation was performed with the assistance
147 of OpenCV software (Intel, US).

148 4. The rendered image 3 was superimposed on the image 1 and displayed on the monitor.

149

150 **Experiment 2**

151 Data collection, processing and 3D modeling of organs

152 Elbow (1/2 of upper arm ~ 1/2 of forearm) of a Japanese monkey cadaver was
153 used for this experiment. The X-ray CT data of the cadaveric elbow was used with
154 modeled frame data that could be precisely attached to the humerus and ulna on the
155 posture at 90 degrees elbow flexion, 90 degrees forearm pronation. The frame was printed
156 on a 3D printer (Davinci 1.0A / XYZ Printing, Inc. US.) using Acrylonitrile butadiene
157 styrene plastic. The frame was then fixed to the cadaver elbow with epoxy resin to ensure
158 that it could not be easily moved. (Fig. 3a)

159 X-ray CT and MRI of elbow and the frame were performed and these datasets
160 were used to obtain the bone and nerve data using methods similar to experiment 1. We
161 obtained bone segmentation from the CT data and nerve segmentation from the MRI data
162 of a cadaveric Japanese monkey elbow. Segmentation and refinement were performed

163 using the VoTracer software (Riken, Wako, Japan). All segmented lesion data was
164 exported as STL data. (Fig. 3b)

165

166 Setup of elbow arthroscope and device tracking system.

167 Tracking system setup was similar to experiment 1 except that we added an anti-
168 pollution barrier on the system. Washable stainless-steel base plate was constructed to
169 stabilize the elbow frame, and placed at different markers on the baseplate and the
170 arthroscopy camera head. Relative position between the baseplate and elbow frame was
171 static. 3D model base plate and arthroscopy camera body loci data was provided by
172 MicronTracker3. The rendered images were superimposed on the real-time view and
173 displayed on the AR monitor.

174

175 Augmented reality image processing during training surgery

176 Elbow arthroscopy surgery was performed on the monkey elbow through
177 anteromedial and posterior portals. While operating on the cadaver elbow, AR calculated
178 C image was superimposed onto the arthroscopic video by the same method as described
179 in experiment 1. Reverse distortion correlation was performed using lens distortion matrix.
180 The matrix was pre-calculated using calibration pattern of arthroscopy camera.

181

182 AR position error calculation

183 The AR range of error was examined to evaluate the accuracy of the AR system.
184 A checkerboard and marker were superimposed to calculate the range of error. A
185 checkerboard printed on a cardboard and a pre-settled virtual marker were superimposed
186 to calculate registration errors. Distances between the centers of the markers were set to
187 be same as the checkerboard lattice span, and the precision of the super-imposition were
188 examined at 1 cm and 2 cm scope-object distances (Fig.4).

189

190 **Results**

191 We successfully performed AR arthroscopy for the full-size 3D elbow model. The
192 CG data was superimposed onto the elbow arthroscopy video in real-time. We performed
193 a registration to co-visualize the image of the patient's elbow structures and the CG made
194 using preoperative images. After manual modification of the position, scale, and
195 orientation, the accuracy of the superimposed CG data was deemed acceptable on the AR
196 monitor.

197 AR arthroscopy of the cadaveric Japanese monkey elbow was performed (Fig.5a).
198 Humeroradial joint and Radial nerve were superimposed on the real-time view and

199 showed on the AR monitor. Although Radial nerve was not seen on the scope monitor as
200 it was located behind the joint capsule, the position of the radial nerve was clearly
201 observed. This was helpful to the surgeon in creating a lateral portal thereby avoiding
202 radial nerve injury (Fig. 5b).

203 The CG position and shape were initially different due to lens distortion. However,
204 the CG position and shape were corrected to match the arthroscopic view using lens
205 distortion parameters, which were estimated from the calibration pattern in experiment 2
206 (Fig. 6). The AR position and shape errors were 2.3 mm at 1 cm scope–object distance
207 and 3.6 mm at 2 cm scope-object distance.

208

209 **Discussion**

210 We have successfully integrated AR technology with elbow arthroscopy. We have
211 demonstrated the workings of the system and the accuracy of this AR system was deemed
212 satisfactory. Through further iterations and refinements, AR-enhanced arthroscopic
213 visualization has the potential to be a transformative technology. This technique will
214 contribute in reducing the risk of serious complications associated with elbow arthroscopy.

215 The rapid development of endoscopy has enabled minimally invasive surgeries.
216 However, this technique has a spatial perception disadvantage. The surgeon needs to

217 alternate between the macroscopic view of the surgical field and the endoscopic view. AR
218 navigation has recently been employed during brain, spinal, plastic, maxillofacial, and
219 several other highly technically demanding surgeries⁶⁻⁸. However, few studies have
220 focused on its use in upper limb arthroscopy⁹. There is an unmet need for the next-
221 generation arthroscopy system especially designed for the elbow, due to high incidences
222 of associated intraoperative complications.

223 Creating AR-enhanced navigation requires 3D preoperative imaging of the target
224 tissue, AR display, tracking system, and a software to calculate the arthroscopy position
225 and direction for each 3D organ.

226 VoTracer is software employed for volume computer aided design (VCAD) of
227 pre-operative CT and MRI data. Segmentation and refinement of bones and nerves data
228 can be performed using this software. A limitation associated with all VCAD softwares
229 is the need for manual work in creating CG of the target tissue. Fine anatomical
230 knowledge of the elbow, especially of nerve route is required to complete segmentation
231 and refinement of the tissues.

232 There are several methods of display for AR. See-through glasses and 3D
233 projection mapping are possible AR displays. See-through glasses have a drawback that
234 it is difficult to obtain an accurate AR view superimposed on the real view. The see-

235 through glasses need to track the pupil positions in real-time for registration. 3D
236 projection mapping is another way to display AR view. In order to obtain an AR view on
237 the patient skin, the video projector has to be set over the patient in the operating room.
238 As both deep and superficial structures are displayed on the skin surface, a significant
239 error of perception is noted when more than two surgeons see the AR display⁷. We
240 employed a video-based display with two monitors for real arthroscopic view and the AR-
241 enhanced view. This system was a natural fit for arthroscopy as the surgeon could
242 simultaneously confirm the real and AR-enhanced view.

243 A variety of tracking systems are available for clinical settings e.g. infrared
244 camera-based tracking, the tag video tracking, and electromagnetic tracking^{10,11}.
245 Accuracy of the tracking device is very important in clinic as it is directly linked to safety.
246 We used an optical tracking device, MicronTracker3. It was able to trace each target
247 information in real-time using a customized software developers' kit. Accuracy of this
248 tracking system was deemed acceptable and the position and shape error was 2.3 mm at
249 a 1 cm scope-object distance.

250 Arthroscopy simulator training improves performance of students and residents
251 during knee and shoulder surgery¹²⁻¹⁴. Recently, multiple types of virtual reality based
252 training simulators for arthroscopy have been reported¹⁵. Among those simulators, high-

253 fidelity virtual reality simulation was reported to be superior compared to the low-fidelity
254 model to acquire arthroscopic skills¹⁶. AR enhanced arthroscopic system with
255 superimposed tasks can be a high-fidelity training tool for surgical education. This system
256 can also provide a third person view using the stereo camera on the optical tracking device,
257 MicronTracker3. Third person view and record of tracking markers provide a trainee
258 feedback regarding handling of scope and other instruments during surgery.

259 AR enhanced navigation for arthroscopy may become the next generation
260 arthroscopy system. However, there are some limitations in this study. First, we used
261 preoperative imaging techniques such as CT and MRI but not real-time information of
262 the target tissue. The size and location of the lesion at the time of surgery may differ from
263 preoperative data. Second, the elbow flexion angle was fixed in our experiments, however
264 surgeons in a clinical setting typically move the elbow during arthroscopy. Superimposed
265 CG data therefore needs to change according to the elbow angle. AR with real-time data
266 of the target tissue is required to solve these problems. Intraoperative CT, MRI, or
267 ultrasonography may be employed to obtain intraoperative data of the target tissue.
268 Actually, nerves around the elbow can be clearly visualized using ultrasonography^{17,18}. In
269 addition algorithm for intraoperative data is required.

270

271 **Conclusions**

272 The technological integration of AR with arthroscopy was successful. We attained
273 satisfactory accuracy and demonstrated the workings of such a system. Upon resolution
274 of some limitations, the AR-enhanced arthroscopic visualization has the potential to
275 become the next-generation arthroscopy. Elbow arthroscopy procedure requires
276 significant training for surgeons, and even skilled surgeons have reported complications
277 during surgery. We believe that AR-enhanced arthroscopy will reduce the risk of serious
278 complications associated with elbow arthroscopy.

279

280 **Abbreviations**

281 AR: augmented reality

282 CT: computed tomography

283 MRI: magnetic resonance imaging

284 3D; 3-dimensional

285 CG: computer graphics

286 STL: Standard Triangulated Language

287 VCAD: volume computer aided design

288

289 **References**

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336

337 **Declarations**

338 **Ethics approval and consent to participate**

339 The study protocol was approved by the Ethics Committee of Nagoya University Hospital
340 (2020-0013). Informed consent was obtained from all participants in this study. All
341 methods in this study were performed in accordance with relevant guidelines and
342 regulations.

343

344 **Consent for publication**

345 Not applicable.

346

347 **Availability of data and materials**

348 The datasets during the current study available from the corresponding author on
349 reasonable request.

350

351 **Competing interests**

352 The authors declare no competing financial and non-financial interests.

353

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359

360 **Contributions**

361 MY, SO, and HY have full access to all of the data in the study and take responsibility for
362 the integrity of the data and the accuracy of the data analysis.

363 Study concept and design: MY and HY

364 Acquisition of data: MY, SO, SO, and YM

365 Analysis and interpretation of data: MY and HH.

366 Drafting of the manuscript: MY and SO

367 Critical revision of the manuscript for important intellectual content: MY and HH

368 Administrative, technical, or material support: SO, YM and HY

369 Study supervision: MY, HH, and HY

370 All authors have read and approved the final submitted manuscript.

371

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374 party related directly or indirectly to the subject of this article.

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376

377 **Figure legends**

378 **Fig.1** A real size 3-dimensional (3D) model of organs and frame.

379 The model was made by using a Standard Triangulated Language (STL) 3D printer
380 (Object500 Connex, Stratasys Ltd, US.).

381

382 **Fig.2** Elbow arthroscopy and tracking device system.

383 Red arrows indicate Xpoints (a). The Schema of augmented reality (AR) Arthroscopy
384 System (b).

385

386 **Fig.3** Elbow of a Japanese monkey cadaver and Standard Triangulated Language (STL)
387 data.

388 We used the elbow (1/2 of upper arm ~ 1/2 of forearm) of Japanese monkey cadaver.

389 From X-ray computed tomography (CT) data of the cadaveric elbow, we modeled frame

390 data that can be precisely attached to humerus and ulna on the posture of 90 degrees elbow

391 flexion, 90 degrees forearm pronation (a). We obtained bone segmentation from CT data
392 and nerves from magnetic resonance image (MRI) data of a cadaveric Japanese monkey
393 elbow. Segmentation and refinement were performed by using VoTracer software (Riken,
394 Wako, Japan) (b).

395

396 **Fig. 4** Augmented reality (AR) system alignment and registration error calculation and
397 calibration

398 The error distance was examined at 1 cm and 2 cm scope–object distances to determine
399 the effect of viewing distance. A checkerboard and marker were superimposed to
400 calculate error.

401

402 **Fig. 5** Augmented reality (AR) arthroscopy on cadaveric Japanese monkey elbow.

403 Capitellum and radial head were visualized through anteromedial portal and visualized
404 on the scope monitor (a). Humeroradial joint and Radial nerve (white arrows) were
405 superimposed on the real view (b). Red arrow indicates a third person view using the
406 stereo camera on the optical tracking device.

407

408 **Fig. 6** Reverse distortion correction using lens distortion matrix.

409 White arrows show differences between before and after correction. Appropriate
410 distortion of the shape on the monitor was corrected.