Segmentation and Determination of Joint Space Width in Foot Radiographs

O. Schenk*[1], D.M. de Muinck Keizer[1], H.J. Bernelot Moens[2], C.H. Slump[1]
[1]MIRA Institute for Biomedical Technology and Technical Medicine, University of Twente, Enschede, The Netherlands, [2]Department of Rheumatology, Ziekenhuisgroep Twente, Hengelo, The Netherlands.

ABSTRACT

Joint damage in rheumatoid arthritis is frequently assessed using radiographs of hands and feet. Evaluation includes measurements of the joint space width (JSW) and detection of erosions. Current visual scoring methods are time-consuming and subject to inter- and intra-observer variability. Automated measurement methods avoid these limitations and have been fairly successful in hand radiographs. This contribution aims at foot radiographs.
Starting from an earlier proposed automated segmentation method we have developed a novel model based image analysis algorithm for JSW measurements. This method uses active appearance and active shape models to identify individual bones. The model compiles ten submodels, each representing a specific bone of the foot (metatarsals 1-5, proximal phalanges 1-5).
We have performed segmentation experiments using 24 foot radiographs, randomly selected from a large database from the rheumatology department of a local hospital: 10 for training and 14 for testing. Segmentation was considered successful if the joint locations are correctly determined. Segmentation was successful in only 14%. To improve results a step-by-step analysis will be performed.
We performed JSW measurements on 14 randomly selected radiographs. JSW was successfully measured in 75%, mean and standard deviation are 2.30±0.36mm.
This is a first step towards automated determination of progression of RA and therapy response in feet using radiographs.

Keywords: RA, segmentation, AAM , JSW

INTRODUCTION

Rheumatoid arthritis (RA) is an inflammatory disease causing swelling, pain and stiffness leading to loss of function in joints. Commonly affected joints are the small joints in hands, wrist and feet. Current treatments focus on pain relief, inflammation reduction and therefore reducing joint damage. To reduce joint damage detection in an early stage is essential.

Joint damage in RA is frequently assessed using radiographs of hands and feet. Evaluation includes measurements of the joint space width (JSW) and detection of erosions. Current visual scoring methods, as used in clinical research[1,2], are time-consuming and subject to inter- and intra-observer variability[3,4]. Improved treatment strategies have reduced joint damage and the currently used scoring methods are falling short in sensitivity to detect the minimal changes in early arthritis.

* o.schenk@utwente.nl, telephone: +31 (0) 53 489 4371

Medical Imaging 2016: Computer-Aided Diagnosis, edited by Georgia D. Tourassi, Samuel G. Armato III,
Proc. of SPIE Vol. 9785, 97853G · © 2016 SPIE · CCC code: 1605-7422/16/$18 · doi: 10.1117/12.2216873

Computerized methods to measure JSW in hand radiographs have been proposed [5–9]. These systems have been fairly successful, reducing subjectivity, measuring on a metric scale with a higher sensitivity and improved reproducibility [7,10–16]. However automated quantification of bone loss and erosion in hand joints has only been demonstrated in a few cases using μCT and MRI[17].

The aim is to develop automated methods to measure joint damage (JSW, erosions) with a higher sensitivity to change compared to the currently used visual scoring methods.

This paper focuses on the first step of automatic measurements on foot radiographs: segmentation and JSW measurements, in which individual joints are located and JSW is measured (semi-)automatically. The long term goal of this algorithm is fully automated quantification of disease progression in RA.

METHOD

A fairly successful method for automatic segmentation on hand radiographs was developed by Kauffman et al. [18,19] We have now redesigned this method for foot radiographs. We use a set of ten foot-radiographs (anteroposterior view) randomly selected from a large database from the rheumatology department of a local hospital for training. We have selected another 14 foot radiographs from the same database for testing. Inclusion criteria were; maximal one radiographs per patient, only radiographs made from one foot, radiographs made after the first of December 2012. Pixel size was 10 pixels per millimeter.

In order to use left and right feet images in a single model, the left-foot images were mirrored. Foot radiographs usually include the tarsals as well as the metatarsals and phalanges. For damage assessment only the metatarsal-phalangeal joints (MTP) 1-5, interphalangeal joint (IP) are evaluated. Therefore, we preprocess the images by removing redundant –and most likely disturbing- information. We manually indicated the upper left corner of the proximal phalanx and the right lower corner of the cropped image containing metatarsal 1-5 and proximal phalanges 1-5. The box defined by the x- and y-coordinates of these points is used for further analysis.

The segmentation method uses multiple connected active appearance models (AAM)[20–22]. We use 10 connected submodels each representing an individual phalanx (metatarsals 1-5, proximal phalanges 1-5), since these are the six joints per foot that are also included in the visual scoring (MTP 1-5, IP 1). The model for individual bones was created using manually outlined contours using a custom made application, that allows to place 64 equally distributed landmarks on each of the contours with the help of an earlier developed “fish bone” shaped grid[18]. This “fish bone” also helps define corresponding landmark positions of multiple images (Figure 1-2).

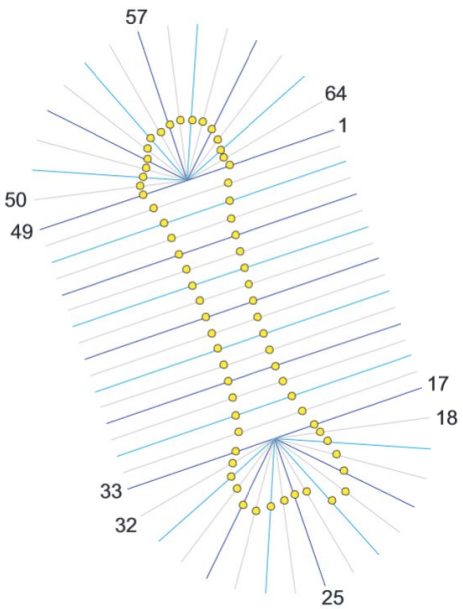

Figure 1 The 'fish bone' shaped grid, which is used to place 64 equally distributed points. The grid is placed based on manually indication of the ends of a bone. The radiating grid lines originate at 15% of the bone length from both ends. [18]

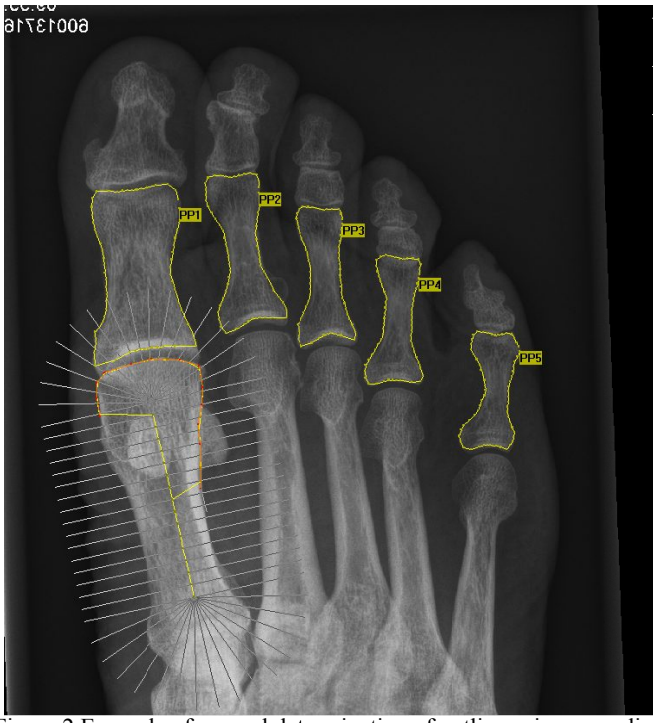

Figure 2 Example of manual determination of outline using an earlier developed 'fish bone' shaped grid[18]. Proximal phalanges 1-5 are already drawn, the drawing of metatarsal 1 in progress. These manually outlined contours are used to make the model. The grid is placed manually selecting the proximal and distal ends of a bone.

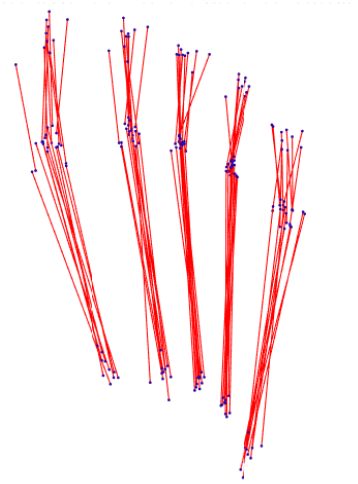

Figure 3 Variability of positioning of phalanges of the feet included in the model, shown using a wireframe model of the training set.

The model includes information about shape, intensity values and relative positioning of the phalanges of the training data (Figure 3). Output is a contour and associated surrounding box for each phalangeal bone. Segmentation was considered successful if visual inspection showed that the location of the joints MTP1-5 and IP1 were determined correctly.

To perform JSW measurements, a region of interest (ROI) is created using the outcome of the segmentation. This ROI is 25x25 mm and should contain the whole joint and the joint space should be placed in the center of the ROI. When segmentation failed, the location of the joint was manually indicated. Joint margins are determined using 30 profile plots in y-direction equally distributed along 6 mm in the middle of the ROI. Next, the profile plots are used to detect the joint space (darkest point along profile). The first and last 75 points of the profile plot are ignored to avoid errors due to high and low intensity values from the bone marrow. The distal margin is detected as first local maximum distal from the darkest point. The proximal margin is detected as the first local maximum higher than 108.5% of the darkest point are detected (Figure 4-5). This number was experimentally determined.

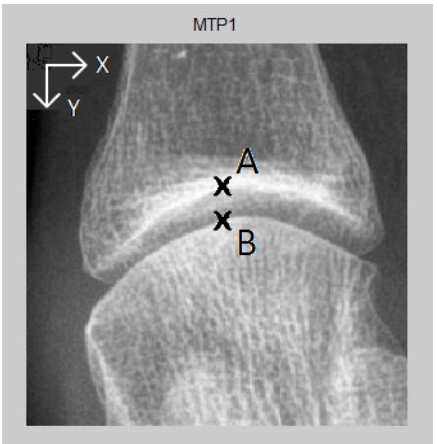

Figure 4 ROI of joint, detected distal point (A) and detected proximal point (B)

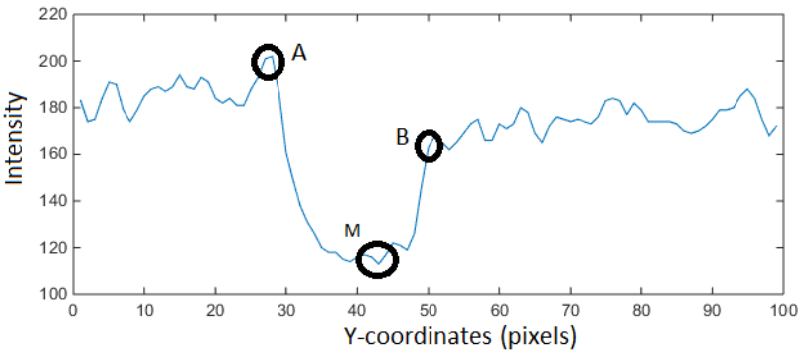

Figure 5 Example of a profile plot, circles represent darkest point (M), detected distal point (A) and detected proximal point (B)

Incorrectly detected points are corrected using the statistical mode (the value that appears most often). We assume the orientation of the joint to be vertically and therefore the joint margins to be horizontal. We allow small deviations; detected points 5mm more distal or 16mm more proximal than the mode are excluded. Furthermore, points with a difference >5mm with respect to the medial point next to it are excluded.

RESULTS

The first step is the segmentation. In Figure 6 an example is given of the outcome of the segmentation algorithm.

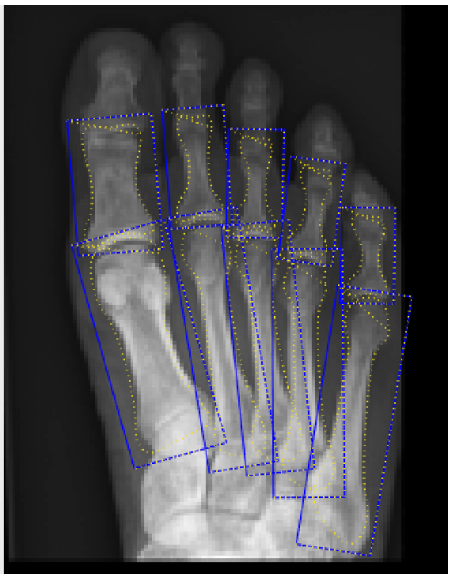

Figure 6 Example of outcome of the segmentation algorithm; in blue the surrounding boxes, in yellow the contours

Automatic segmentation was correct in 12 joints (14%). Joint locations were manually indicated when automatic segmentation failed so JSW measurements could be performed on all joints.

JSW measurements were evaluated by a rheumatologist (HM). 51% was considered correct. 24% was considered ”almost correct”, 15% completely wrong. In 10% the program failed to automatically determine joint margins (Table 1). Examples of the different kinds of joint margins are shown in Figure 7-9.

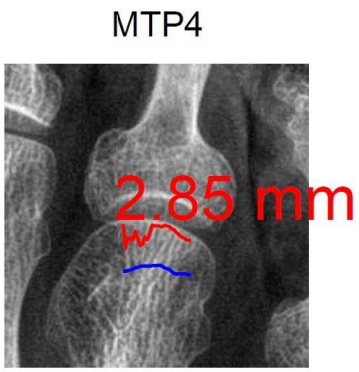

Figure 7 Example of wrongly delineated joint (red: distal margin, blue: proximal margin)

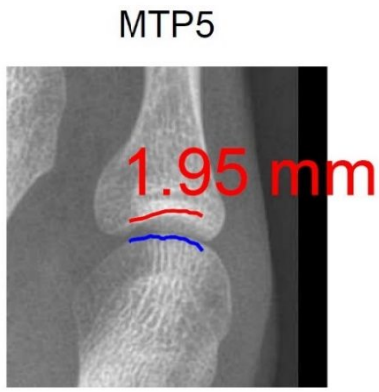

Figure 8 Example of "almost correct" determined joint margin (red: distal margin, blue: proximal margin)

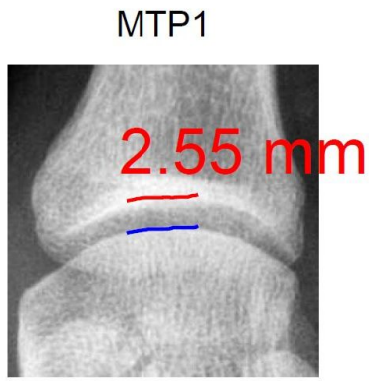

Figure 9 Example of correctly determined joint margin (red: distal margin, blue: proximal margin)

The program failed to automatically determine joint margins due to the wrongly determined joint space along the profile plot. We assumed the joint space to be the minimum along the profile, however, in some cases the minimum is located inside the bone structure (Figure 10).

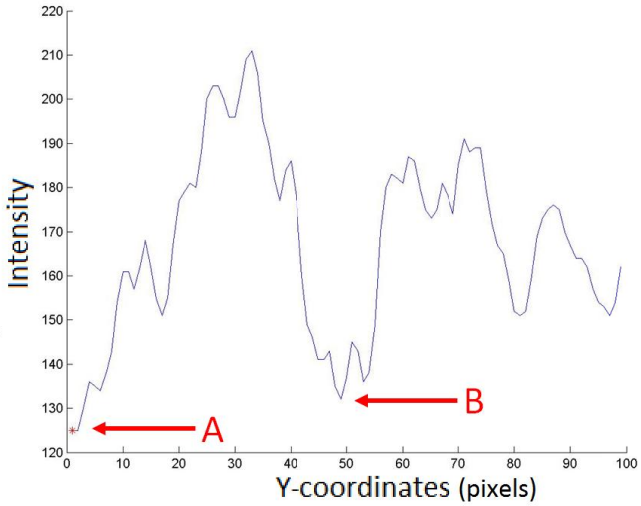

Figure 10 Example of wrongly determined joint space (A) with respect to the real joint space (B)

Mean and standard deviation (std) are calculated using only correct determined joint margins (Figure 11, Table 2).

Table 1 Results of JSW measurements

	MTP1	MTP2	MTP3	MTP4	MTP5	IP1
Correct	7 (50%)	11 (%)	7 (50%)	6 (43%)	7 (50%)	5 (36%)
”Almost Correct”	1 (7%)	3 (21%)	5 (36%)	5 (36%)	4 (29%)	2 (14%)
Completely wrong	2 (14%)	0 (0%)	1 (7%)	1 (7%)	3 (21%)	6 (43%)
Program failure	4 (29%)	0 (0%)	1 (7%)	2 (14%)	0 (0%)	1 (7%)

Table 2 Mean and standard deviation values of foot joints, values in millimeter

	MTP1	MTP2	MTP3	MTP4	MTP5	IP1	Total
Mean-std	2.22	2.39	2.11	1.95	1.74	1.77	1.94
Mean	2.39	2.69	2.28	2.18	1.99	1.90	2.30
Mean+std	2.57	2.98	2.44	2.41	2.23	2.02	2.65

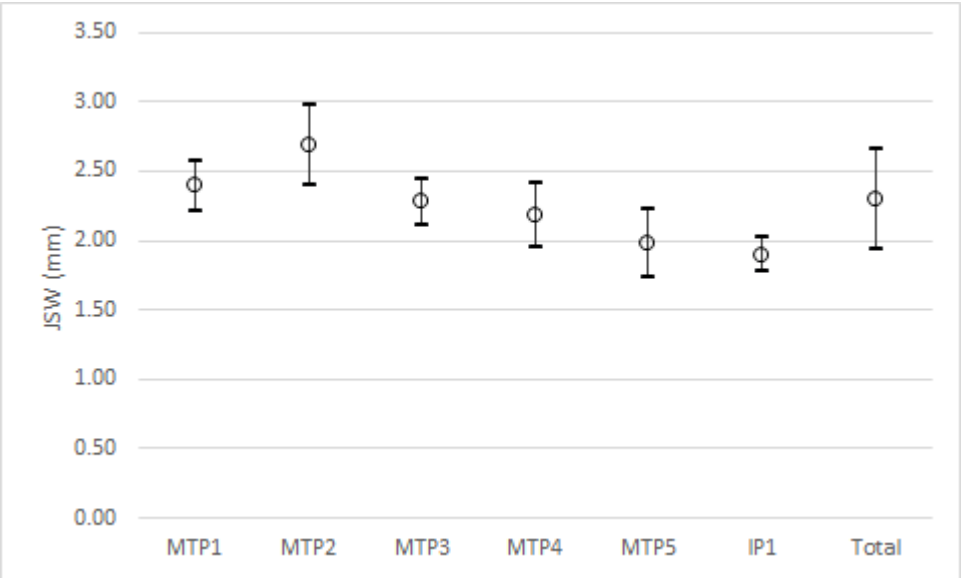

Figure 11 Mean and standard deviation values of foot joints

DISCUSSION

The radiographs have been manually preprocessed, however, using a positioning aid might provide tools to automatically perform the preprocessing.

Although our segmentation method successfully determined 14% of our test data, we believe that this method should perform much better since a the AAM-method used on hand radiographs is able to correctly find over 73% of all bone contours[18]. Causes of failures of the automatic segmentation method will be determined using a step-by-step analysis. Our JSW measurement method successfully determined joint margins in 51%. We are confident that we are able to improve our JSW measurement method; using a different definition of an "incorrectly detected point" and therefore allowing larger deviations. Also, we will investigate how to improve the determination of the joint space along the profile plots, since this caused failure to determine joint margins in 15%. Our aim should be to correctly determine joint locations and identify joint margins in over 80%.

The determined JSW values are plausible. We did not find literature to compare our measurements against. Foot radiographs are currently made using a projection angle (angle of the path of an x-ray with regard to the orientation of the exposed object) of 15 degrees. This may reflect in errors in consecutive JSW measurements as well as erosion detection[23,24]. Although it is not yet known how large these errors are in feet, further standardizing acquisition using for example a positioning aid is expected to improve outcome. Still, this is a first step establishing normal values for feet joints as are already established in hand joints [25,26]. Since individual JSW values are irrelevant in the assessment of disease progression, they differ per person, method for automated determination of progression of RA can be used to assess changes over time.

CONCLUSIONS

We described and tested methods to automatically locate and measure the distance of joint of the foot using radiographs. The segmentation method is based on an earlier developed AAM-based method for segmentation of hand radiographs.[18]

We evaluated the segmentation method and automatic JSW measurement method using 14 randomly selected radiographs. As in currently used scoring methods for damage assessment in RA, we addressed only MTP 1-5 and PIP 1. The segmentation method was able to correctly find 12 out of 84 joint locations. Joint margins were correctly found in 51%. Failures of the automatic JSW measurement method were caused by incorrectly found joints space.

This is a first step towards automated determination of progression of RA in feet using radiographs. Next steps are improving the algorithms and to involve the addition of automatic erosion detection on foot radiographs.

REFERENCES

[1] Van Der Heijde, D., "How to read radiographs according to the Sharp/van der Heijde method," J. Rheumatol. **27**, 261–263 (2000).

[2] Heijde, D. van der., Dankert, T., Nieman, F., Rau, R.., Boers, M., "Reliability and sensitivity to change of a simplification of the Sharp/van der Heijde radiological assessment in rheumatoid arthritis.," Rheumatology (Oxford). **38**(10), 941–947 (1999).

[3] Boini, S.., Guillemin, F., "Radiographic scoring methods as outcome measures in rheumatoid arthritis: properties and advantages.," Ann. Rheum. Dis. **60**(9), 817–827 (2001).

[4] Guillemin, F., Billot, L., Boini, S., Gerard, N., Ødegaard, S.., Kvien, T. K., "Reproducibility and sensitivity to change of 5 methods for scoring hand radiographic damage in patients with rheumatoid arthritis.," J. Rheumatol. **32**(5), 778–786 (2005).

[5] Buckland-Wright., Carmichael, I.., Walker, S. R., "Quantitative microfocal radiography accurately detects joint changes in rheumatoid arthritis.," Ann. Rheum. Dis. **45**(5), 379–383 (1986).

[6] van 't Klooster, R., Hendriks, E. A., Watt, I., Kloppenburg, M., Reiber, J. H. C.., Stoel, B. C., "Automatic quantification of osteoarthritis in hand radiographs: validation of a new method to measure joint space width.," Osteoarthr. Cartil. **16**(1), 18–25 (2008).

[7] Sharp, J. T., Angwin, J., Boers, M., Duryea, J., Ingersleben, G. Von., Hall, J. R., Kauffman, J. A., Landewé, R., Langs, G., et al., "Computer Based Methods for Measurement of Joint Space Width : Update of an Ongoing OMERACT Project," J. Rheumatol. **34**(4), 874–883 (2007).

[8] Huo, Y., Vincken, K. L., Viergever, M. A.., Lafeber, F. P., "Automatic joint detection in rheumatoid arthritis hand radiographs," Proc. - Int. Symp. Biomed. Imaging, 125–128, Utrecht (2013).

[9] Pfeil, A., Böttcher, J., Seidl, B. E., Schäfer, M. L., Hansch, A., Heyne, J.-P., Petrovitch, A., Mentzel, H. J., Eidner, T., et al., "Computer-aided joint space analysis (CAJSA) of the proximal-interphalangeal joint-normative age-related and gender specific data.," Acad. Radiol. **14**(5), 594–602 (2007).

[10] Böttcher, J., Pfeil, A., Rosholm, A., Sörös, P., Petrovitch, A., Schaefer, M. L., Seidl, B. E., Malich, A., Hansch, A., et al., "Computerized quantification of joint space narrowing and periarticular demineralization in patients with rheumatoid arthritis based on digital x-ray radiogrammetry.," Invest. Radiol. **41**(1), 36–44 (2006).

[11] Neumann, G., DePablo, P., Finckh, A., Chibnik, L. B., Wolfe, F.., Duryea, J., "Patient repositioning reproducibility of joint space width measurements on hand radiographs.," Arthritis Care Res. (Hoboken). **63**(2), 203–207 (2011).

[12] Angwin, J., Heald, G., Lloyd, A., Howland, K., Davy, M.., James, M. F., "Reliability and sensitivity of joint space measurements in hand radiographs using computerized image analysis.," J. Rheumatol. **28**(8), 1825–1836 (2001).

[13] Buckland-Wright., "Radiographic assessment of osteoarthritis: comparison between existing methodologies.," Osteoarthritis Cartilage **7**(4), 430–433 (1999).

[14] Angwin, J., Lloyd, A., Heald, G., Nepom, G. T., Binks, M. H.., James, M. F., "Radiographic hand joint space width assessed by computer is a sensitive measure of change in early rheumatoid arthritis," J. Rheumatol. **31**(6), 1050–1061 (2004).

[15] Finckh, A., de Pablo, P., Katz, J. N., Neumann, G., Lu, Y., Wolfe, F.., Duryea, J., "Performance of an automated computer-based scoring method to assess joint space narrowing in rheumatoid arthritis: a longitudinal study.," Arthritis Rheum. **54**(5), 1444–1450 (2006).

[16] Pfeil, A., Renz, D. M., Hansch, A., Kainberger, F., Lehmann, G., Malich, A., Wolf, G.., Böttcher, J., "The usefulness of computer-aided joint space analysis in the assessment of rheumatoid arthritis.," Joint. Bone. Spine **80**(4), 380–385 (2013).

[17] Scharmga, A., van Tubergen, A., van den Bergh, J., de Jong, J., Peters, M., van Rietbergen, B.., Geusens, P., "SAT0165 Cortical Breaks and Bone Erosions in the Hand Joints: A Cadaver Study Comparing Conventional Radiography with High-Resolution and Micro-Computed Tomography," Ann. Rheum. Dis. **73**(Suppl 2), 650–650 (2014).

[18] Kauffman, J. A., Slump, C. H.., Bernelot Moens, H. J., "Segmentation of hand radiographs by using multi-level connected active appearance models," Proc. SPIE **5747**, J. M. Fitzpatrick and J. M. Reinhardt, Eds., 1571–1581 (2005).

[19] Bernelot Moens, H. J., Kauffman, J. A.., Slump, C. H., "Automated analysis of hand radiographs by using multi-level connected appearance models," Ann. Rheum. Dis. **64**(3) (2005).

[20] Cootes, T. F., Hill, A., Taylor, C. J.., Haslam, J., "Use of active shape models for locating structures in medical images," Image Vis. Comput. **12**(6), 355–365, Elsevier (1994).

[21] van Ginneken, B., Frangi, A. F., Staal, J. J., ter Haar Romeny, B. M.., Viergever, M. A., "Active shape model segmentation with optimal features," IEEE Trans. Med. Imaging **21**(8), 924–933 (2002).

[22] Stegmann, M. B., Fisker, R., Ersboll, B. K., Thodberg, H. H.., Hyldstrup, L., "Active Appearance Models : Theory and Cases," 1–9 (2000).

[23] Withaar, T. T., Kauffman, J. A.., Bernelot Moens, H. J., "Analyzing the precision of JSW measurements using 3D scans and statistical models," Proc. SPS-DARTS 2006 Second Annu. IEEE Benelux/DSP Val. Signal Process. Symp. Antwerp, Belgium(1), 123–126 (2006).

[24] Segerink, L., Withaar, T. T., Lansbergen, M. D. I., Kauffman, J. A., Schimmelpenninck-Scheiffers, M. L.., Bernelot Moens, H. J., "Standardisation of hand x-rays for arthritis: the relevance of hand positioning," Ann. Rheum. Dis. 65 (Suppl 2)., 593 (2001).

[25] Pfeil, A., Hansch, A., Lehmann, G., Eidner, T., Schäfer, M. L., Oelzner, P., Renz, D. M., Wolf, G., Hein, G., et al., "Impact of sex, age, body mass index and handedness on finger joint space width in patients with prolonged rheumatoid arthritis using computer-aided joint space analysis.," Rheumatol. Int. **29**(5), 517–524 (2009).

[26] Pfeil, A., Böttcher, J., Schäfer, M. L., Seidl, B. E., Schmidt, M., Petrovitch, A., Heyne, J.-P., Lehmann, G., Oelzner, P., et al., "Normative reference values of joint space width estimated by computer-aided joint space analysis (CAJSA): the distal interphalangeal joint.," J. Digit. Imaging **21 Suppl 1**, 104–112 (2008).