Intraoperative measurement of mechanical axis alignment by automatic image stitching: a human cadaver study

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Motivation: The mechanical axis of the lower limb is a straight line defined by the center of the femoral head and the center of the ankle joint, ideally passing the knee joint in its center. Deviation of the knee center from this line can lead to knee disorders such as osteoarthritis. The distance of the knee center from the mechanical axis is defined as the mechanical axis deviation (MAD). The accurate intraoperative verification of the MAD helps to verify alignment for reconstructive surgery as well as trauma surgery of long bones of the lower limb. Out of the operating room, the alignment is usually determined using the long standing radiograph of the complete lower limbs. Intraoperatively however, alternative methods are needed such as the electrocautery cord method or X-ray grid method to verify the mechanical axis alignment [1, 4]. These conventional methods require considerable X-ray images, surgeon experience, and cannot provide metric measurements. Navigation systems that provide metric measurements have been employed for intraoperative analysis of lower limb alignment, showing an improved accuracy and reliability compared to conventional methods [2]. Nevertheless, none of navigation systems has been widespread accepted for routine clinical use, mainly because of their hefty cost, a cumbersome system setup including line of sight for tracking and on-site calibration, and difficult system registration.

The aim of this study was to evaluate the practicability, validity and reproducibility of a newly developed system that helps to confirm alignment faster and with less X-ray dose.

Materials & Methods: We have developed a computer assisted intraoperative X-ray stitching method that can calculate the MAD and therefore the alignment by placing only three X-ray images into a panoramic image frame. Our protocol requires the X-ray images to cover the femoral head, the knee and the ankle. The registration of the three X-ray images to the panorama is realized by an optical video camera attached to the C-arm's X-ray source viewing a visual marker pattern underneath the operating table and a computer running our software [3]. Additional hardware or calibration during surgery is not required.

19 human cadaver legs were manually bent to induce a random valgus or varus malalignment while keeping the knee fully extended. Each individual leg was positioned in a wooden box and placed on a carbon table with a visual marker pattern of 2378 x 1682 mm rigidly attached underneath it. The leg positioning was such that the patella faces upwards (confirmed by X-ray). The modified C-arm was translated along the carbon table in a PA gantry position for acquiring the three X-ray images. To reduce parallax effects and enable accurate MAD measurements, (i) the bone plane had to be roughly parallel to the planar marker pattern and (ii) the distance between the marker plane and the bone plane had to be estimated with the help of a ruler [3].

Three X-ray images of femoral head, the knee and the ankle were acquired and subsequently stitched together using the method described in [3]. A CT scan of each leg was conducted immediately afterwards in order to attain a ground truth reference for comparison. The CT scout image was defined as ground truth since it provides an image with proper metric properties of an equal non weight-bearing setup with the leg lying on the table. Three observers with different surgical experience levels (i.e. senior and resident surgeon, medical student) were involved in our study. The anatomical landmarks defining the mechanical axis and the knee center were manually determined by each observer individually for all of the CT images and panoramic X-ray images in order to allow MAD calculation.

Results: First, the mean MAD values attained by CT (14.75 ± 9.16 mm) and by C-arm stitching (13.25 ± 7.66 mm) were calculated. Secondly, we computed the Pearson correlation coefficient that exhibited a highly significant correlation between ground truth CT and our method ($r = 0.96$, $p < 0.01$). The individual observer measurements for all legs are shown in the attached Table 1.

1	Ground-truth CT (mm)	X-ray stitiching (mm)	Δ in mm
Leg 1	31,60	29,15	2,45
Leg 2	22,70	18,14	4,56
Leg 3	10,70	9,20	1,50
Leg 4	14,90	14,45	0,45
Leg 5	17,30	13,35	3,95
Leg 6	13,70	11,17	2,53
Leg 7	31,60	28,16	3,44
Leg 8	10,10	8,29	1,81
Leg 9	23,90	21,85	2,05
Leg 10	16,70	15,03	1,67
Leg 11	3,00	2,60	0,40
Leg 12	6,00	8,02	2,02
Leg 13	19,10	9,94	9,16
Leg 14	25,10	22,32	2,78
Leg 15	6,60	8,56	1,96
Leg 16	9,00	14,24	5,24
Leg 17	5,70	6,83	1,13
Leg 18	12,50	5,70	6,80
Leg 19	0,00	4,57	4,57
mean			3,08
std			2,22

2	Ground-truth CT (mm)	X-ray stitiching (mm)	Δ in mm
Leg 1	31,00	28,38	2,62
Leg 2	20,30	17,20	3,10
Leg 3	10,80	11,64	0,84
Leg 4	16,70	16,07	0,63
Leg 5	19,70	12,64	7,06
Leg 6	17,30	13,32	3,98
Leg 7	32,20	28,77	3,43
Leg 8	10,20	8,11	2,09
Leg 9	23,90	18,69	5,21
Leg 10	18,50	17,59	0,91
Leg 11	0,00	6,00	6,00
Leg 12	8,40	11,57	3,17
Leg 13	19,10	14,72	4,38
Leg 14	25,70	24,62	1,08
Leg 15	4,80	9,57	4,77
Leg 16	8,40	13,10	4,70
Leg 17	4,20	6,86	2,66
Leg 18	7,80	5,18	2,62
Leg 19	0,00	2,42	2,42
			3,25
			1,80

3	Ground-truth CT (mm)	X-ray stitiching (mm)	Δ in mm
Leg 1	31,7	28,42	3,28
Leg 2	24,5	21,93	2,57
Leg 3	6,6	8,89	2,29
Leg 4	17,3	16,48	0,82
Leg 5	16,1	13,23	2,87
Leg 6	16,1	11,21	4,89
Leg 7	32,2	31,86	0,34
Leg 8	11,9	14,62	2,72
Leg 9	24,5	22,38	2,12
Leg 10	13,7	15,04	1,34
Leg 11	1,8	3,63	1,83
Leg 12	3	7,09	4,09
Leg 13	13,7	11,34	2,36
Leg 14	24,6	22,56	2,04
Leg 15	6,6	7,09	0,49
Leg 16	6,6	10,38	3,78
Leg 17	4,8	9,5	4,7
Leg 18	6	6,37	0,37
Leg 19	0	4,5	4,5
			2,49
			1,45

Expert surgeon	3
Resident surgeon	2
Medical student	1

Conclusions: Existing methods and solutions for intraoperative exact alignment control demand a high level of surgeon experience since both hip, knee and ankle centers have to be located in the center of the X-ray along with the grid or electrocautery cable [1, 4]. This results in a large amount of X-ray shots, radiation exposure and effort. Our proposed technique requires only three X-ray images to be acquired, thereby also reducing procedural time. Via a one-time ruler measurement of the distance between marker pattern and knee, parallax effects are reduced. As a result, neither the hip, nor knee or the ankle must be centered in the images, still allowing accurate intraoperative MAD measurements. We showed the reproducibility and validity of the calculated data by comparing it to the ground truth CT and having it evaluated by different skill groups. We await ethics board approval for patient study evaluation.

References

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