

A novel set-up for the automation of a video fluoroscope to retrieve in vivo knee joint kinematics during level walking

Mauro Foresti, Hans Gerber, Monika Zihlmann, Edgar Stuessi
Laboratory for Biomechanics, Dep. of Mechanical and Process Engineering
ETH Zurich
Zurich, Switzerland
mforesti@ethz.ch

Abstract— X-Ray video fluoroscopy is nowadays a common technique to retrieve in vivo 3D kinematic data of the knee joint during human motion activities. Unfortunately, since a fluoroscopic imaging system is designed to be stationary during measurement, the knee joint moves out of field of view of the fluoroscope during level walking. Therefore, it becomes unfeasible to retrieve scientifically useful images of the knee over an entire gait cycle, which is essential for a complete biomechanical analysis of the knee joint movement. The method presented here shows a new system that enables the continuous acquisition of in vivo kinematic data of the human knee joint during several cycles of standard level walking. The set-up consists of a C-arm video fluoroscope and an automated mobile robot unit which tracks the position of the knee relative to the fluoroscope in order to constantly keep the knee in the field of view of the imaging unit.

Keywords: *In vivo kinematics; Knee; Fluoroscopy; X-rays; Gait analysis; 2D- to-3D registration.*

I. INTRODUCTION

In the past decade, a great deal of effort has been put into assessing the kinematics of the knee joint by means of X-ray video fluoroscopy. Despite the radiation the test subject has to experience, this method allows an accurate insight of the knee kinematics [2, 3, 4, 6, 8]. Compared to skin-mounted-marker based gait analysis [1], video fluoroscopy totally eliminates skin-motion-artifacts issues, because it allows a direct observation of the joint components. However, this innovative technique shows a remarkable drawback: a limited field of view. Hence, the number of human movements that can be studied in order to gain useful biomechanical information of the knee is also restricted. Therefore, it becomes rather difficult to make any statement about knee functionality during everyday activities, e.g. walking.

At first sight, a solution could be to perform fluoroscopy based gait analysis on a treadmill. Doing so, two salient problems arise: 1. the gait pattern is altered compared to the undisturbed situation [7, 9], 2. simultaneous retrieval of ground reaction forces becomes unfeasible. Therefore, we developed a system that is able to track the position of the knee relative to the field of view of the fluoroscope and keeps the moving

equipment at the distance that provides an optimal imaging of the bones in the articulation during several gait cycles.

II. MATERIALS AND METHODS

A. Single-plane video fluoroscopy equipment

The video fluoroscope used for measurement corresponds to a complete fluoroscopic medical system operating at clinical standards (BV Pulsera, Philips Medical Systems, Switzerland). The C-arm, consisting of an image intensifier and a X-ray source, was detached from the X-ray generator and equipped with a 8 m long cable to allow for a greater independent movement. The arm of the fluoroscope was then fixed on a robot cart for movement controlling (Fig. 1).

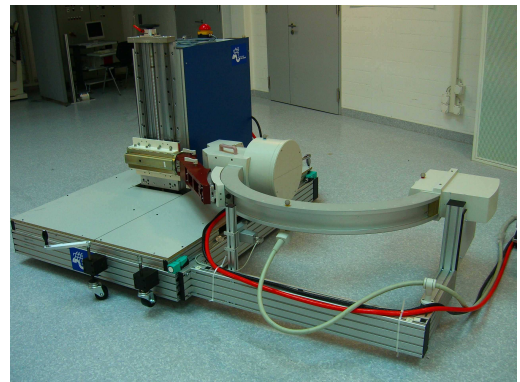


Figure 1. Front view of the robot unit with C-arm

The image intensifier has a diameter of 12 inches and contains a CCD camera with 752x582 effective pixels. The storage matrix accounts to 768x576 pixels. The system allows for X-ray video-recording of up to 25 frames per second with a shutter time of 8 milliseconds.

B. Robot unit

1) Mechanical specifications

The robot unit consists of a four-wheeled cart with a vertical linear-motion slide carrying the C-arm of the video fluoroscope. The first prototype, which has been used successfully for a pilot study [10, 11], consisted of a single

motor driving only one of the two live axles connecting two wheels each. Since the maximum speed and acceleration accounted only for slow walking subjects (max. speed: $\sim 2.5\text{m/s}$; max. acceleration: $\sim 5\text{m/s}^2$), a new design concept had to be developed. The new prototype has a motor for each wheel. One motor acts as a master, while the others are synchronized to the position of the former, thus creating two electric live axles connected together. The new moving system, fluoroscopic arm included, weighs approximately 450kg.

2) Tracking and controlling specifications

A draw wire sensor fixed underneath the C-arm on the robot unit measures the position of the knee relative to the center of the imaging unit. The sensor is directly connected to an external computer which records the measurement instantly. The computer exploits this knowledge to drive the motors according to a proportional-integral-derivative (PID) controller to keep the knee joint in the field of view of the video fluoroscope.

3) Security system

Since the measurements involve human beings, the robot unit has been built to be double fail-safe. Furthermore, once the direction of measurement has been set, the moving equipment cannot change its course, unless the trial is aborted and the system is reset. This prevents the robot unit to invert direction and run into the subject, who is walking right in the middle of the C-arm.

C. Photogrammetry equipment

The photogrammetry equipment is a VICON system (Oxford Metrics Inc., Oxford, UK) consisting of 8 fixed and 4 mobile cameras. Three reflective markers are attached at well predefined spots on the C-arm in order to assess the position of the fluoroscope in the laboratory coordinate system. Redundant reflective markers are also placed on the subject's extremities.

D. Synchronization

In order to ensure a synchronization between the photogrammetry measurements and the fluoroscopic imaging, the activation pulse sent by the X-ray generator to the X-ray source is galvanically isolated and routed to an analog input channel of the VICON equipment.

E. Reference frame calibration and 2D-to-3D reconstruction

X-ray images coming from the fluoroscopic equipment are usually distorted and thus need correction. Before each measurement, a well-defined calibration grid is placed right in front of the image intensifier to evaluate the distortion parameters. Since the grid intersection points are known, the transformation matrix from the grid reference frame to the fluoroscopic images can be directly calculated. The same grid is also used to compute the position and orientation of the fluoroscopic image with regard to the laboratory reference frame by fixing it at a well-measured location.

After having assessed the transformations between the different reference frames, the three-dimensional kinematic information of the knee joint can be determined by a

subsequent 2D-to-3D reconstruction. At first, a digital-reconstructed radiograph (DRR) is computed out of the volume information of the joint, and then a least-squares based algorithm locates its relative pose in space by comparing the DRR with the actual X-ray fluoroscopic image [3].

III. CONCLUSIONS

This abstract has shown a novel method to acquire X-ray video fluoroscopy data of the knee joint during level walking. The measuring setup is able to track the knee at any instance in time during several consecutive gait cycles. The maximum speed and acceleration reached by the whole moving system corresponds to $\sim 3.5\text{m/s}$ and $\sim 8\text{m/s}^2$ respectively¹.

By means of a 2D-to-3D reconstruction algorithm, the 3D kinematics of the knee can accurately be assessed with regard to the laboratory reference frame. Furthermore, by combining the measurement system presented here with a simultaneous acquisition of the ground reaction forces, it becomes possible to conduct a thorough mechanical study of the femorotibial and patellofemoral joints during every-day human motion activities[5].

REFERENCES

- [1] T. P. Andriacchi, C. O. Dyrby, T. S. Johnson, "The use of functional analysis in evaluating knee kinematics", *Clin Orthop Relat Res* (410): 44-53, 2003.
- [2] S. A. Banks, W. A. Hodge, "Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy", *IEEE Trans Biomed Eng* 43 (6): 638-649, 1996
- [3] K. V. Burckhardt, "Locating implants with respect to the bone in diagnostic x-ray images of the pelvis", Ph.D. thesis, Swiss Federal Institute of Technology, Zurich 2002.
- [4] D. A. Dennis, M. R. Mahfouz, R. D. Komistek, and W. Hoff. "In vivo determination of normal and anterior cruciate ligament-deficient knee kinematics.", *J Biomech*, 38(2): 241-53, 2005.
- [5] H. Gerber, M. Zihlmann, M. Foresti, E. Stuessi, "Method to simultaneously measure 3D kinematic and kinetic data during normal level walking using Kistler force plates, Vicon System and video-fluoroscopy", 2006, unpublished.
- [6] G. Li, L. E. DeFrate, H. E. Rubash, T. J. Gill, " In vivo kinematics of the ACL during weight-bearing knee flexion", *J Orthop Res* (23): 340-344, 2005.
- [7] M. P. Murray, G. B. Spurr, S. B. Sepic, G. M. Gardner, and L. A. Mollinger. "Treadmill vs. floor walking: kinematics, electromyogram, and heart rate". *J Appl Physiol*, 59(1):87-91, 1985.
- [8] R. Stagni, S. Fantozzi, A. Cappello, and A. Leardini. "Quantification of soft tissue artefact in motion analysis by combining 3d fluoroscopy and stereophotogrammetry: a study on two subjects." *Clin Biomech* 20(3):320-9, 2005.
- [9] G. M. Strathy, E. Y. Chao, and R. K. Laughman. "Changes in knee function associated with treadmill ambulation." *J Biomech*, 16(7):517-22, 1983.
- [10] M. Zihlmann, H. Gerber, K. V. Burckhardt, A. Stacoff, E. Stussi, "Three dimensional in vivo kinematics of artificial knee joints during level walking using a moving video-fluoroscope", in: *Canadian Society for Biomechanics, 13th Conference, Halifax, Nova Scotia, Canada, 2004.*
- [11] M. Zihlmann, H. Gerber, A. Stacoff, K. Burkhard, G. Szekey, E. Stüssi, "Three dimensional kinematics and kinetics of total knee arthroplasty during level walking using single plane video-fluoroscopy and force plates: A pilot study", in press.

¹ An ongoing study at our laboratory over 20 subjects showed that system can robustly track the knee to keep it in the field of view of the video fluoroscope.