Journal of Biomechanics 49 (2016) 3741–3745

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Characterizing fluoroscopy based kinematic accuracy as a function of pulse width and velocity

Arin M. Ellingson [a,b,e], Joseph D. Mozingo [b,c], Dixon J. Magnuson [d], Mark W. Pagnano [a], Kristin D. Zhao [b,c,*]

[a] *Department of Orthopedic Surgery, Mayo Clinic, Rochester, MN, USA*
[b] *Department of Physical Medicine and Rehabilitation, Mayo Clinic, Rochester, MN, USA*
[c] *Biomedical Engineering and Physiology Graduate Program, Mayo Graduate School, Rochester, MN, USA*
[d] *Department of Radiology, Mayo Clinic, Rochester, MN, USA*
[e] *Department of Rehabilitation Medicine, University of Minnesota, Minneapolis, MN, USA*

ARTICLE INFO

Article history:
Accepted 16 September 2016

Keywords:
Knee
Joint kinematics
Fluoroscopy
Accuracy
Agreement
Pulse width
Arthroplasty
Knee replacement

ABSTRACT

Fluoroscopic imaging has become increasingly popular to investigate total knee arthroplasty kinematics non-invasively – 3D implant models are aligned with 2D image projections, and optimized via an edge-contour alignment technique. Previous studies have quantified the accuracy of this approach, however they do not always adequately address the impact of image collection parameters. A particularly sensitive parameter is the pulse width, or exposure time per frame. At longer pulse widths, more motion is captured in a single frame; this can lead to image blur and subsequent degradation to image edge quality. Therefore, the comparative accuracy of relative joint kinematics as a function of pulse width and joint velocity needs to be defined. A limits of agreement approach was taken to define the mean differences between optoelectric kinematic measures (gold standard) and fluoroscopic methods at various pulse widths (1, 8 and 16 ms) and knee velocities (50, 100 and 225°/s). The mean absolute differences between the optoelectric and fluoroscopic methods for 1 ms pulse width were less than 1.5° and 0.9 mm. Comparable rotational differences (1.3°) were observed for the 8 ms pulse width but had larger translational differences (1.4 mm). The 16 ms pulse width yielded the greatest mean differences (2.0° and 1.6 mm), which increased with knee flexion velocity. The importance of pulse width and velocity should not be overlooked for future studies – this parameter has proven to be a sensitive metric in the quantification of joint motion via fluoroscopy and must be identified and reported in future studies.

1. Introduction

Fluoroscopic imaging has become an increasingly popular method to investigate total knee arthroplasty (TKA) kinematics non-invasively using shape-matching techniques. Briefly, the position and orientation of a 3D implant model is aligned with 2D image projections of its X-ray and optimized via an edge-contour alignment algorithm (Fig. 1) (Mahfouz et al., 2003). Prior studies aimed to assess the accuracy of this shape-matching technique have reported absolute accuracies on the order of a millimeter and sub-degrees (Banks and Hodge, 1996; Mahfouz et al., 2003; Yamazaki et al., 2004). Relative joint kinematics has reported errors of less than 2.1° and 1.9 mm using a single plane fluoroscopy system (Acker et al., 2011; Lebel et al., 2011). It is important to note that many of these studies determine accuracy based on a foam model of the bones without soft tissue – an idealistic case without added noise from surrounding musculature and skin. Internal validation experiments are a critical step prior to clinical research. However, many recent studies have not performed their own validation, but rely on previously published accuracy measurements, which may not reflect the accuracy of their own system and process (Fujimoto et al., 2016; Nakamura et al., 2015; Okamoto et al., 2014). Furthermore, inexperienced fluoroscopy research teams may utilize available clinical units, for which parameters are often difficult to customize. The lack of customizability may result in lengthened or automatic exposure times not controlled or reported by the researcher. Therefore, without proper knowledge of one's own equipment and attention to detail, inadequate data can be collected and thus improper conclusions potentially made. Another critical

* Correspondence to: Rehabilitation Medicine Research Center, Assistive and Restorative Technology Laboratory, Department of Physical Medicine and Rehabilitation, Mayo Clinic, Rochester, MN 55905 USA.
E-mail address: zhao.kristin@mayo.edu (K.D. Zhao).

http://dx.doi.org/10.1016/j.jbiomech.2016.09.044
0021-9290/

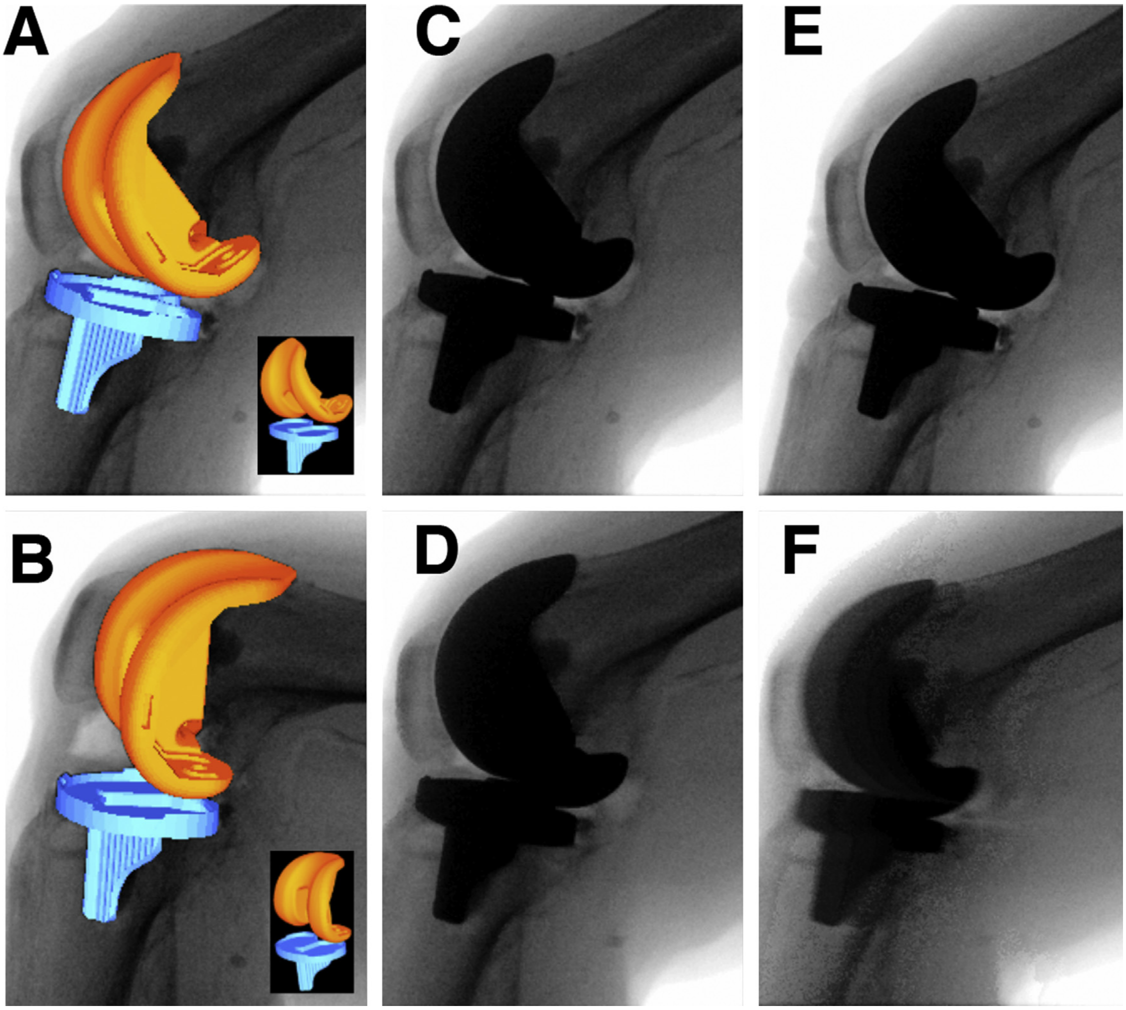

Fig. 1. Workflow of 2D/3D Shape Matching. Left: 3D TKA models aligned with silhouette when knee is initially fully extended (A) and fully flexed (B). Middle: silhouette of 1 ms pulse width at initial position (C) and position of maximal flexion velocity (D). Right: silhouette of 16 ms pulse width at initial position (E) and at maximal flexion velocity (F).

component often lacking in recently published work are the study's fluoroscopic imaging parameters, which likely have a significant effect on kinematic accuracy.

A particularly sensitive parameter in dynamic imaging with fluoroscopy is the pulse width, or exposure time per frame. In an effort to reduce radiation to as low as reasonably achievable (ALARA) levels, many fluoroscopy systems use a pulsed sequence, rather than continuous exposure with no shutter. The length of the pulse width is simply analogous to the exposure time per frame, and is directly related to the amount of motion that can occur within the frame. At longer pulse widths, a greater amount of motion is captured in a single frame at a given object's velocity; this can lead to image blur and subsequent degradation to image edge quality – a critical factor for the shape-matching technique. The importance of this phenomenon has been nicely, yet anecdotally described previously (Tashman, 2008). However, to our knowledge, no studies have quantified the errors associated with increased pulse widths and movement velocity. *Therefore, the purpose of this study was to assess the accuracy of 6 degree-of-freedom relative TKA kinematics as pulse width and flexion velocity were systematically varied.*

2. Methods

With the approval from our institutional biospecimens committee, one intact, fresh–frozen male (91 yr) cadaver right leg was acquired from the Mayo Clinic Bequest Program. Appropriately sized femoral (size 5) and tibial (size 4) total knee replacement components (Triathlon® knee system, Stryker Orthopaedics, Mahwah, NJ, USA) were implanted by an orthopedic surgeon using a standard surgical approach. To facilitate digitization, small slits in the skin on the medial and lateral aspects of the femur and tibia were created to expose landmarks used to establish local anatomical coordinate systems (Grood and Suntay, 1983).

The proximal femur and distal tibia were potted in bone cement and secured upright in a custom apparatus that allowed for unconstrained knee flexion (30–80°), which mimicked passive rotation of the knee immediately post-operation at a manually guided rate. Fig. 2 illustrates the apparatus and set-up. The linear slide attached to the proximal end of the femur translates vertically and the ankle brace distally allows plantar and dorsiflexion of the foot permitting rotation of the knee joint. The knee was centered in the imaging volume created by the 30 × 38 cm flat-panel Multi-Diagnost Eleva C-arm single-plane fluoroscopy system (Philips Medical Systems, Best, Netherlands) perpendicular to the primary plane of bending (sagittal plane) with a source to image-receptor distance of 1250 mm. Images were collected at a resolution of 512 × 512 pixels (0.746 mm/pixel). X-ray images were acquired at 30 Hz (63 kV, 160 mA) with varying pulse widths – 1 ms, 8 ms, and 16 ms.

Active infrared marker sets were attached to bone pins that were embedded in the femur and tibia (Ilharreborde et al., 2010). 3D kinematics were simultaneously acquired using an Optotrak Certus at 100 Hz (Northern Digital Inc., Waterloo, Ontario, Canada) and subsequently downsampled to 30 Hz using a custom Matlab script (Matlab®, MathWorks, Natick, MA, USA). The optoelectric system has reported accuracy on the order of 0.2° and 0.15 mm (Baltali et al., 2008; Ilharreborde et al., 2010). The flexion rotation data was used to align the two systems temporally through a point set registration technique utilizing a least squares regression to minimize the differences in the datasets – visual inspection of each dataset confirmed synchronous frames of initial motion for each system. Using a metronome, the knee rotation velocity was varied between 50°/s, 100°/s, and 225°/s in a randomized fashion for each pulse width investigated, which resulted in approximately 120 frames, 60 frames, and 20 frames, respectively since the collection frequency was