Measurement of Skeletal Kinematics from Fluoroscopy: Techniques, Validation and Accuracy for Real-World Applications

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Accurate measures of musculoskeletal kinematics are essential for understanding the function of healthy joints, the impact of injury or disease, and the effectiveness of orthopaedic treatment. Dynamic radiography is the only currently available imaging modality that offers the potential for:

- High frame rates
- Sub-mm accuracy
- Freedom from skin motion artifact
- Testing of dynamic, functional, high-loading motion activities (e.g. walking, running, jumping, throwing, etc)

The advantages of this technology are now widely recognized, as evident from the growing number of laboratories that either have or are developing radiographic systems for kinematic studies. These vary considerably in hardware and analysis techniques, ranging from a single conventional C-arm fluoroscopy unit (commonly available in most hospitals) to custom-designed configurations that can provide biplane imaging for a wide variety of movements and joints. The accuracy of these systems varies with design and application, and has in general not been well characterized. A lack of consensus in this relatively young field as to how these systems should be evaluated has also made direct comparisons between systems difficult. The goals of this symposium talk are to discuss some of the design considerations for dynamic radiographic imaging systems, consider different approaches for evaluating measurement accuracy, and report some of our efforts to characterize performance during real-world applications.

X-ray based motion analysis is complex, expensive and exposes subjects to ionizing radiation. Thus, its use is justified only for studies that require greater measurement accuracy than more conventional methods. Examples include investigations of in-vivo ligament function or cartilage-level interactions of the articulating surfaces of a joint. These applications require tracking six degree-of-freedom bone pose with accuracy consistently better than 1 mm/1 degree. Single-plane fluoroscopy systems have not been able to achieve this level of accuracy, due to uncertainty of position along the direction of the x-ray beam. This requires a priori assumptions to be made about the “important” movement directions, and dictates image views (e.g. sagittal) that may be prone to limb/bone overlap. Biplane systems can provide consistently high 3D accuracy and robust tracking. However, actual performance depends upon a number of factors related to the hardware design, analytical methods and specific application.

Dynamic biplane imaging system hardware should be designed to achieve:

- The best possible x-ray image quality
- The largest possible field of view
- Freedom of movement within the imaging area
- Positioning flexibility to enable imaging of a variety of joints/movements

These goals are often conflicting. C-arm systems are readily available and easy to use, but tend to restrict freedom of movement. The gantry system used at Henry Ford offers a large area of unrestricted movement, at the cost of more limited flexibility for imaging configuration.

Image quality is highly dependent on both hardware configuration and application. It varies with imaging system properties (noise, contrast, resolution), radiographic protocol (kVp, mA), exposure time per frame, source-subject-detector distance, density of imaged tissues and limb movement speed. Higher x-ray power leads to better-quality images, particularly for fast movements where short exposure times are essential to minimize image blur. Many commercial fluoroscopy systems were designed primarily for static imaging, and are inappropriate for dynamic studies. High-power, high frequency pulsed x-ray generators can significantly reduce radiation dose while maximizing image quality.

The level of image quality necessary to achieve accurate 3D bone tracking depends upon the method used to extract 3D information from the x-ray image pairs. Radio-stereophotogrammetric (RSA) methods, employing implanted fiducial markers (e.g. tantalum beads), can achieve very good accuracy (±0.1 mm) even from relatively noisy, low-resolution images. However, recent efforts have focused on techniques utilizing some form of model or shape-based tracking, as they do not require an invasive procedure for marker implantation. These techniques vary considerably in technical approach, but all are much more dependent on image quality, particularly for identifying edges between bone and soft tissue as well as internal bone features. Methods previously applied for tracking metal implants (e.g. for TKA) may not be suitable for natural bone tacking, due to the huge difference in relative radiographic contrast between bone and high-density metals. Performance may also depend on bone size, density and shape, the volume of surrounding soft tissue and the presence of overlapping objects in the image field. The influences of these various factors on tracking accuracy are difficult to predict *a priori* for a particular application.

Thus, it is essential that validations be performed to determine performance for each hardware/software system under *real-world* conditions, i.e. for the bones/joints in their natural configuration (including overlap with other bones/soft tissues, etc), moving at appropriate speeds, using radiographic protocols approved for *in vivo,* human use. Validation requires a “gold standard” for comparison; repeatability studies alone do not assess accuracy. This presents a significant challenge for *in vivo* validations. However, reasonable results can be achieved using a high-precision positioning system to move a joint *ex vivo*, provided the testing adequately simulates the real-world conditions described above.

An attractive alternative is to use a tracking technique of established accuracy for comparison with model-based radiographic tracking, enabling validation during arbitrary joint motions. Using our previously validated dynamic RSA methods, we are able to evaluate tracking performance for nearly any motion or joint, either *in vivo* or *in vitro*. We have completed accuracy studies for the tibio-femoral joint, the patello-femoral joint and the gleno-humeral joint, with demonstrated accuracy in the range of 0.2 to 0.5 mm in translation and 0.3 to 1.6 degrees in rotation. We have also shown that soft tissue/bone overlap and image quality can have a significant effect on real-world measurement accuracy. These results further support the need for joint, application and system-specific validation of x-ray based measurement methods.