INTRODUCTION
Fluoroscopic imaging has become an increasingly popular method to investigate total knee arthroplasty (TKA) kinematics non-invasively. Briefly, 3D implant models are aligned with 2D image projections, and optimized via an edge-detection algorithm (Fig. 1). Prior studies aimed to assess the accuracy of this shape-matching technique, though largely ignore the importance of fluoroscopic imaging parameters [1, 2]. A particularly sensitive parameter in dynamic applications is the pulse width, or exposure time per frame, which if too long may lead to blur (Fig. 1F) and subsequent degradation in image edge quality. This phenomenon has been anecdotally described previously [3]. 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 TKA kinematics as pulse width and flexion velocity were systematically varied.

METHODS
One intact, fresh-frozen cadaver right leg was acquired from the Mayo Clinic Bequest Program. Femoral and tibial total knee replacement components (Triathlon® Knee System, Stryker Orthopaedics, Mahwah, NJ, USA) were implanted by an orthopedic surgeon. A portion of the knee was left partially exposed to facilitate digitization of landmarks to establish local anatomical coordinate systems.

The femur and tibia were secured in a custom apparatus that allowed for unconstrained knee flexion at a manually guided rate. The knee was centered in the imaging volume created by the 48 cm flat-panel Multi-Diagnost Eleva C-arm single-plane x-ray system (Philips Medical Systems, Best, Netherlands) perpendicular to the primary plane of bending. X-ray images were acquired at 30 Hz (63 kV, 160 mA). Infrared marker sets were attached to bone pins that were embedded in the femur and tibia. 3D kinematics were simultaneously acquired using an Optotrak Certus (Northern Digital Inc., Waterloo, Ontario, Canada) and subsequently downsampled to 30 Hz. The rotation rate was varied between 50°/s, 100°/s, 225°/s for pulse widths of 1ms, 8ms, and 16ms.

An open source model-based tracking program was used to manipulate the position and orientation of 3D CAD models of the femoral and tibial components, such that model edges were coincident with edges of the projected silhouettes on the radiograph (JointTrack, University of Florida, Gainesville, FL, USA). Following manual placement, poses were optimized with a built-in simulated annealing algorithm [4]. Relative orientation was defined using Euler angles (Z-X-Y sequence; flexion/extension, abduction/adduction, external/internal rotation) [5]. The 3D position and orientation of the tibia relative to the femur were determined for all frames of each trial and the limits of agreement were defined using a Bland-Altman technique.

RESULTS AND DISCUSSION
The average kinematic differences between the optoelectric and fluoroscopic methods for the
optimal 1ms pulse width was 1.2° and 0.6 mm or less for all trials (Table 1). Figure 2 depicts a Bland-Altman plot demonstrating the agreement between the two kinematic collection techniques. A linear trend was only detected in the abduction rotation (R²=0.73). The overall largest mean differences were in abduction-adduction across trials, but varied in translation.

Comparable mean differences and agreement were observed for the 8ms pulse width – less than 1.2° and 0.8mm (Table 1).

The 16 ms pulse width yielded the greatest mean differences, which were intensified during the most dynamic flexion activity. The mean rotational and translational differences were nearly double (2.0°) and triple (1.6mm) those from 1ms, respectively. Furthermore, the agreement between the systems, represented by the confidence interval, also increased dramatically for the 16ms pulse width.

CONCLUSIONS
In conclusion, this work defines the accuracy of our fluoroscopy system in conjunction with a 2D/3D shape-matching protocol for TKA models, which was well below previously acceptable levels [2]. This provides a basis for future trials investigating TKA kinematics in vivo.

Additionally, the importance of pulse width and velocity should not be overlooked for future studies – greater than 1ms pulse widths should be used cautiously and pulse widths of 16ms and greater avoided. 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.

REFERENCES

ACKNOWLEDGEMENTS
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Table 1 Mean differences between methods (bold). The limits of agreement in parentheses (95% confidence interval)

<table>
<thead>
<tr>
<th>Difference</th>
<th>1ms Pulse Width</th>
<th>8ms Pulse Width</th>
<th>16ms Pulse Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 °/s</td>
<td>100 °/s</td>
<td>225 °/s</td>
<td>50 °/s</td>
</tr>
<tr>
<td>Flexion (deg)</td>
<td>-0.1 (-1.4 to 1.3)</td>
<td>1.0 (-0.4 to 2.5)</td>
<td>-0.4 (-2.7 to 1.9)</td>
</tr>
<tr>
<td>Abduction (deg)</td>
<td>-0.5 (-1.9 to 0.8)</td>
<td>-0.4 (-1.7 to 1.0)</td>
<td>-1.2 (-3.9 to 1.5)</td>
</tr>
<tr>
<td>Internal (deg)</td>
<td>-0.4 (-1.9 to 1.0)</td>
<td>-0.1 (-1.7 to 1.4)</td>
<td>-0.4 (-2.5 to 1.8)</td>
</tr>
<tr>
<td>Ant / Post. (mm)</td>
<td>-0.5 (-1.8 to 0.6)</td>
<td>-0.4 (-1.6 to 0.8)</td>
<td>-0.3 (-1.6 to 1.0)</td>
</tr>
<tr>
<td>Sup / Inf (mm)</td>
<td>-0.2 (-0.9 to 0.6)</td>
<td>-0.2 (-0.9 to 1.4)</td>
<td>-0.2 (-1.7 to 1.2)</td>
</tr>
<tr>
<td>Med / Lat (mm)</td>
<td>-0.0 (-1.8 to 1.7)</td>
<td>-0.2 (-2.6 to 2.2)</td>
<td>-0.6 (-2.0 to 0.8)</td>
</tr>
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</table>

Figure 2: Bland-Altman plots. Demonstrate agreement in kinematic measures between fluoroscopic and optoelectronic methods for 1ms pulse width, 50° rotation rate trial. Each point represents the mean and difference of relative joint angles (top row) and translations (bottom row) between each method, at a given frame. The dashed and solid lines are the mean difference between methods, and the 95% confidence intervals respectively.